Bulletin

of

The Geological Society of America

VOLUME 58 June 1947 NUMBER 6

CONTENTS

PAGES

Radioactivity of the rocks of the batholith of southern California. By E. S. Larsen and N. B. Keevil 483-494

Structure plan of the Southern Sierra Nevada, California. By Evans B. Mayo 495-504

Porosity and ore deposition at Edwards and Balmat, New York. By John S. Brown 505-546

Index to Volume 58 (January–June) 547-550

Subscription $10 per year.

Publication Office: Mt. Royal and Guilford Aves., Baltimore 2, Md.

Communications for publication should be addressed to The Geological Society of America, Dr. H. R. Aldrich, Secretary, 419 West 117th Street, New York 27, N. Y.

NOTICE.—Four weeks notice of change of address is necessary. In accordance with the rules established by the Council, claims for non-receipt of the preceding number of the Bulletin must be sent to the Secretary of the Society within three months of the date of the receipt of this number in order to be filled gratis.

Entered as second-class matter in the Post-Office at Baltimore, Md., under the Act of Congress of July 16, 1894.

Accepted for mailing at special rate of postage provided for in Section 1103 Act of October 3, 1917, authorized on July 8, 1918.

PAPERS IN PRESS FOR FORTHCOMING ISSUES

HOLARCTIC MAMMALIAN FAUNAS AND CONTINENTAL RELATIONSHIPS DURING THE CENOZOIC. By G. G. Simpson

CENOZOIC PHYSIOGRAPHIC HISTORY OF THE FRONT RANGE, COLORADO. By E. E. Wahlstrom

CHEMICAL ANALYSES AND CALCULATED MODES OF THE OLIVERIAN MAGMA SERIES, MT. WASHINGTON QUADRANGLE, NEW HAMPSHIRE. By M. P. Billings and J. C. Rabbitt

CAMBRIAN ROCKS OF NORTHEASTERN STEVENS COUNTY, WASHINGTON. By C. D. Campbell

BLACK HAND SANDSTONE AND CONGLOMERATE IN OHIO. By Karl Ver Steeg

ARCHEAN GEOLOGY OF THE TURKU DISTRICT, SOUTHWESTERN FINLAND. By Anna Hietanen

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 58, PP. 483-494 JUNE 1947

RADIOACTIVITY OF THE ROCKS OF THE BATHOLITH OF SOUTHERN CALIFORNIA

BY E. S. LARSEN AND N. B. KEEVIL

CONTENTS

	Page
Abstract	483
Introduction and acknowledgments	484
Southern California batholith	484
Rocks tested	484
San Marcos gabbro	487
Green Valley tonalites	488
Bonsall tonalite and associated rocks	488
Miscellaneous tonalites	488
Woodson Mountain granodiorite	489
Escondido Creek granodiorite	489
Mount Hole granodiorite	489
Granodiorite dike	490
Lake Wolford granodiorite	490
Aplites	490
Granites	490
Miscellaneous rocks	491
Conclusions	491
References cited	493

ILLUSTRATIONS

Figure	Page
1. Geological map of the batholith of the Corona, Elsinore, and San Luis Rey quadrangles, California	485
2. Variation diagram of rocks of the batholith of Southern California	486

ABSTRACT

Determination of radioactivity has been made on 43 rocks, carefully selected from the different mapped units of the complex Cretaceous batholith of Southern California; they range from gabbro to granite. The activity of the gabbro averages about 0.3 alphas/mg./hr., that of the tonalites, 0.8, the granodiorite 1.3, and the granites over 2.0. The activity of the average rock of the batholith is about 0.9 alphas/mg./hr. Most of the rocks have been analyzed, and modal compositions are given. The radioactivity and the percentages of K_2O, SiO_2 and PbO are plotted on a variation diagram. The variation curve for activity nearly parallels that for K_2O, and the ratio of activity to K_2O is about 0.5. The radioactivities of some rocks fall far from the variation curve, and degree of activity correlates with K_2O content. A less-marked correlation between activity SiO_2 and PbO was also noted. The K_2O, SiO_2, PbO, and radioactivity concentrate in the residual liquid during crystallization and differentiation. PbO follows K_2O closely, as it is concentrated in the K_2O minerals, but radioactivity is very low in the K_2O minerals and is greatly concentrated in the accessory minerals.

INTRODUCTION AND ACKNOWLEDGMENTS

This work was partly financed by grants from the Penrose Bequest of The Geological Society of America. Keevil worked at the University of Toronto (Grant 420-42), and Larsen at Harvard University (Grant 381-44).

In this paper the radioactivity (called activity) is expressed in terms of alpha particles per milligram per hour (α/mg./hr.). In terms of U and Th, for equilibrium, one α/mg./hr. results from the disintegration of 0.369 U + 0.0886 Th where U and Th are concentrations in parts per million. The proportions of U and Th in rocks vary, but frequency-distribution curves drawn from several dozen determinations of Th/U show a peak at ± 3.3. If this value is taken for Th/U there is a 50-50 chance that the values for Th or U in parts per million will be within 25 per cent of the values: Th = 5α, U = 1.5α.

SOUTHERN CALIFORNIA BATHOLITH

Most of the rocks for which radioactivity data are given in this report came from the Cretaceous batholith of Southern California, but a few represent somewhat older or somewhat younger rocks. The batholith of Southern California has been described by Larsen in another paper (in press). The batholith has an average width of about 70 miles, a length of at least 500 miles, and a probable length of over 1000 miles. It extends from near Riverside, California, southward into Lower California. A part of the batholith about 70 miles along its length was studied, and the western half of this, about 860 square miles, was mapped and studied in detail. A generalized geologic map of the batholith showing the location of the specimens studied for this report is given (Fig. 1).

In the area studied, the batholith consists of many separate injections, and few of the mapped bodies cover areas as large as 200 square miles. In the area mapped in detail, over 30 rock types are recognized, but 5 of these make up nearly 90 per cent of the batholith, and these 5 types form many separated masses which are distributed throughout the region mapped. Some other types are widespread to the east and south of the mapped areas. In the western half of the batholith the rocks range from gabbro to granite, but the eastern half consists almost entirely of tonalite which is also the chief rock of the batholith as a whole. The intrusion of the magmas, with few exceptions, followed the usual order, beginning with gabbro and followed successively by tonalites, granodiorites, and granites.

Thirty-four rocks from the batholith have been anlyzed, and most of the rocks for which radioactive data are given in this report represent analyzed rocks or those similar to analyzed rocks. Plotted on a variation diagram (Fig. 2) most of the analyses fall very near smooth variation curves; both field and laboratory study show that the rocks are closely related genetically.

ROCKS TESTED

Rocks tested for radiocativity were chiefly those selected for chemical analyses plus a few others. The specimens were carefully selected to represent the different mapped units and, for the large widespread bodies, to represent the various rock

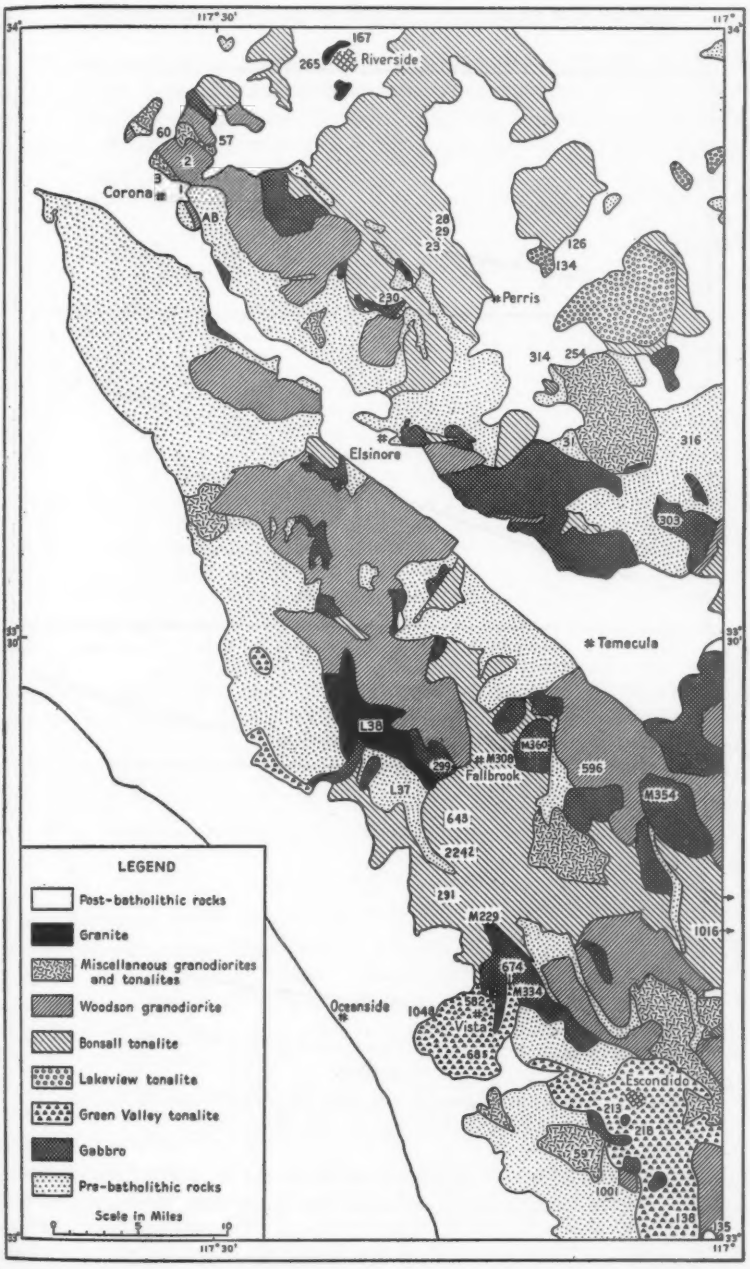


FIGURE 1.—*Geologic map of the batholith of the Corona, Elsinore, and San Luis Rey quadrangles, California*

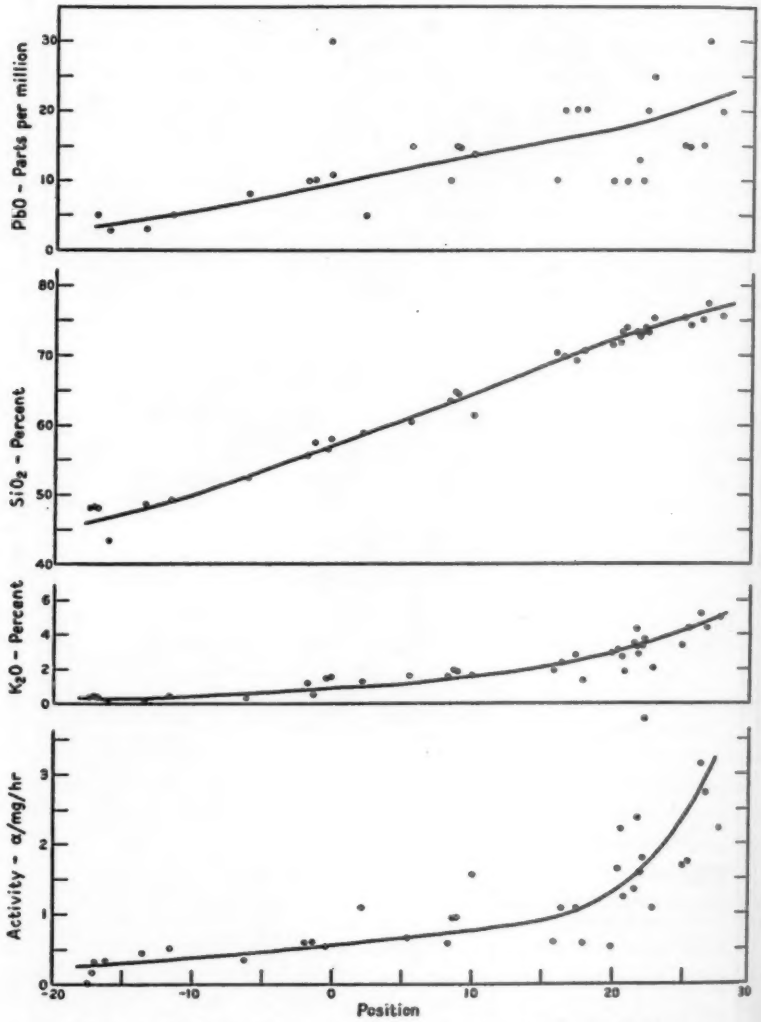


FIGURE 2.—*Variation diagram of rocks of the batholith of Southern California* Showing activity (α/mg./hr.) PbO, SiO_2, and K_2O.

types and the rocks of widely separated bodies in the mapped units. Larsen (in press) describes the batholith and its rocks and gives detailed description of the individual specimens.

The rocks tested are listed and briefly described in the following pages. For some of the rocks several radioactivity determinations were made, each on a separate

sample taken from different hand specimens which were collected from the same locality. These duplicate determinations were sometimes at variance, probably due to the small size of specimens ground for analyses, and to a lesser extent to the small size of the sample actually used in the determinations (0.3 to 0.5 g.). These

TABLE 1.—*Mineral composition and activity of rocks from the San Marcos gabbro*

Number	Quartz	Plagioclase	Biotite	Hornblende	Pyroxene	Olivine	Opaque	Spinel	Activity in alphas/mg./hr.	
									Individual determinations	Average
SLR M354	....	67 (An_{82})	.....	11	2	18	0.2	2	.16, .04, .43	.34
El 303	....	51 (An_{84})	.....	36	9	.....	4.5	....	.36, .13, .09	.19
SLR M3081	....	(An_{88})	.....	near "El 303"		.....	.....	....	.33	.33
SLR M356	....	(An_{88})	.....	near "El 303"		.....	.....	....	.68	.68
SLR M360	....	(An_{87})	.....	near "El 303"		.....	.....	....	.00	.00
SLR 299	....	47 (An_{87})	.....	46	6	.....	2	....	.51, .52, .57	.53
SLR 218	....	61 (An_{89})	1	13	16	.....	8	....	.43	.43
SLR M334	....	65 (An_{84})	.....	1	33	.....	2	....	.33	.33
SLR 229B	7	58 (An_{49})	6	22	6	.....	1	....	.60	.60
SLR 229A	tr.	67 (An_{83})	1	1	28	.....	3	....	.46	.46
El 230	11	54 (An_{85})	13	3	18	.....	.....	....	1.18, 1.49	1.33
Weighed average based on rock outcrops										.43

discrepancies suggest that much larger samples or groups of representative chips should be used to obtain good average values. The remarkable concentration of radioactive elements in certain accessory minerals (Keevil, Larsen, and Wank, 1944) suggests that samples used for analysis should be obtained by the systematic reduction of bulk samples and that sorting of heavier accessory minerals during preparation of samples for radioactivity determinations should be avoided.

SAN MARCOS GABBRO

This formation is known in many small to moderately large bodies in the western half of the batholith from the Mexican boundary 100 miles to the city of Riverside, and is, no doubt, present in Mexico. The mapped unit contains many rock types which range from quartz gabbro to troctolites, and related rocks containing anorthite. Few of the rocks contain olivine, some contain pyroxene, and some hornblende with all proportions of pyroxene and hornblende represented. The textures range from a millimeter or less to several centimeters. Almost every large body of the formation shows a variety of rock types, and often a small hill will contain many of these. The different rocks commonly have sharp, intrusive contacts; some dikelike bodies are only a few inches across, and some bodies of relatively uniform rock underlie several square miles. A detailed description of this formation in the San Luis Rey quadrangle is given by Miller (1937). Eleven rocks from the San Marcos gabbro were tested, and descriptions are given in Table 1. The hornblende and pyroxene rocks show no systematic difference in activity.

GREEN VALLEY TONALITES

The Green Valley tonalite underlies an area of over 100 square miles in the southern part of the San Luis Rey quadrangle and adjoining areas, and a few other small areas. It is a medium-grained rock with few dark inclusions. It is characterized by resorbed cores of bytownite surrounded by andesine, and by hornblende crystals

TABLE 2.—*Mineral composition and activity of rocks from the Green Valley tonalite*

Number	Quartz	Orthoclase	Plagioclase	Amphibole	Biotite	Augite	Hypersthene	Opaque	Activity in alphas/mg./hr.	
									Individual determinations	Average
SLR 582	16	.....	55 (An_{32})	10	8	7	2	3	1.31, .88	1.10
SLR 685	31	12	43 (An_{27})	5	7	.....	.....	2	.....	1.08
SLR 138	24	.....	48 (An_{40})	13	10	3	1	1	.....	.94
SLR 213	22	2	52 (An_{46})	11	10	2	.....	0.5	.....	.93
SLR 674	.....	.....	near 213	.....	.....	.....	.....	.....	.....	.99
Weighed average based on rock outcrops										1.01

which have well-crystallized outer zones and cores of uralitic hornblende with remnants of augite. The calcic cores of the feldspar and probably the cores of the hornblende are remnants of inclusions of gabbro. Data on five of these rocks are given in Table 2.

BONSALL TONALITE AND ASSOCIATED ROCKS

In the area mapped in detail, the Bonsall tonalite covers about 250 square miles which is nearly one-third of the mapped portion of the batholith. It was not found to the east but is abundant south of the mapped area. It occurs as several larger and some smaller bodies and is characterized by abundant flattened, oriented, dark inclusions derived chiefly from the gabbro but now made up of the same minerals as the host. The rock is somewhat coarser in grain than the Green Valley tonalite; calcic cores are very rare in the plagioclase, and the hornblende is well crystallized. The formation grades to a granodiorite.

The Lakeview tonalite occupies one large area in the Elsinore quadrangle and is widespread to the east and southeast. It resembles the Bonsall tonalite but has fewer dark inclusions.

Several small bodies of granodiorite with large orthoclase crystals are associated with the Bonsall tonalite in the Elsinore quadrangle.

The Domenigoni granodiorite underlies an area of about 13 square miles in the Elsinore quadrangle. It carries abundant dark, oriented inclusions. The two rocks tested are darker than the average rock. Data on these rocks are given in Table 3.

MISCELLANEOUS TONALITES

The La Sierra tonalite occupies a few square miles in the hills northeast of Corona. It contains fewer dark minerals than the other tonalites. The rock tested (El 36-57)

contains the following percentages of minerals: quartz 20; microperthite 2; plagioclase (An_{40}) 63; biotite 11; amphibole 3. The activity on a single sample was 1.57.

The tonalite near Aguanga in the Ramona quadrangle underlies a large area. It is fine-grained, of uneven texture, and is rich in quartz and poor in dark minerals.

TABLE 3.—*Mineral composition and activity of rocks from the Bonsall tonalite and associated rocks*

Number	Formation	Quartz	Orthoclase	Plagioclase	Amphibole	Biotite	Sphene	Opaque	Activity in alphas/mg./hr.	
									Individual determinations	Average
El 38-29	Bonsall	....	near El 38-28		.....	.....	.....	.....	.....	1.01
El 38-28	Bonsall	24	.....	55 (An_{45})	8	13	....	....	.....	.57
SLR 1016	Bonsall	12	.....	56 (An_{47})	16	16	....	....	.....	.53
SLR 291	Bonsall	....	near El 38-28		.....	.....	.....	.....	.....	.68
SLR 2242	Bonsall	30	15	40 (An_{32})	8	7	....	....	.....	1.65
El 38-134	Lakeview	22	1	49 (An_{49})	10	19	....	....	.35, .95, .60	.63
El 314	Domenigoni dark variety	32	2	58 ($An_{1.5}$)	5	....	0.5	1	.....	.60
El 254	Domenigoni dark variety	....	lighter colored than El 314		....	....	....	....	.....	.52
El 38-126	Coarse granodiorite	23	12	56 (An_{33})	3	7	....	....	.27, .56, .71	.52
Weighed average based on rock outcrops										.75

The rock tested (Ra 3) contains the following percentages of minerals; quartz 29; alkalic feldspar 6; plagioclase (An_{38}) 51; biotite 8; and apatite 0.01. Determinations of activity on two samples gave 0.64 and 0.53, averaging 0.59 α/mg./hr.

WOODSON MOUNTAIN GRANODIORITE

This is the most widespread granodiorite of the batholith and underlies about 220 square miles in the area mapped in detail. It is abundant to the south but was not found in the eastern half of the batholith. It crops out in many individual areas, the largest of which is about 80 square miles. The rock is coarse-grained and light-colored with a pinkish cast. It is rather uniform in contrast to the tonalites and especially to the gabbros which are variable. Five specimens of this rock scattered over an area about 70 miles long have been tested and are listed in Table 4.

ESCONDIDO CREEK GRANODIORITE

This rock forms several small bodies west of Escondido and underlies about 10 square miles. It is fine-grained and carries abundant, scattered inclusions. The specimen tested (S.L.R.597) was free of inclusions. The minerals and the activity are given in Table 4.

MOUNT HOLE GRANODIORITE

This granodiorite underlies several areas northeast of Corona, a total area of about 3 square miles. It resembles the Woodson Mountain granodiorite but is distinctly

porphyritic. The mineral composition and activity of the sample tested is given in Table 4. Nearly all specimens contain appreciable amounts of allanite.

GRANODIORITE DIKE

In Temescal Wash, a large dike over 1000 feet wide in places cuts the Woodson Mountain granodiorite, and may be related to the Mt. Hole granodiorite. Table 4 includes the mineral composition and the activity of the sample (Cor. 2) tested.

TABLE 4.—*Mineral composition and activity of granodiorites*

Number	Formation	Quartz	Perthite	Plagioclase	Biotite	Hornblende	Opaque	Allanite	Activity in alphas/mg./hr.	
									Individual determinations	Average
El 223B	Woodson near Cor 1.									1.35
SLR 596	Woodson	44	24	28 (An_{32})	2	1	....	....	1.18, 2.25, 1.64	1.7
Cor 1	Woodson	31	19	42 (An_{32})	7	1	....	....	.....	2.4
SLR 1001	Woodson near 596	....	....	.....	....	....	....	....	2.4, 1.17	1.8
Ra 135	Woodson	30	13	52 (An_{34})	3	1	....	....	1.63, 1.69, 1.47	1.6
Average of	Woodson	....	....	.....	....	....	....	....	1.47	1.8
*SLR 597	Escondido Creek	38	11	44 (An_{32})	5	....	1	....	1.17, 131, .73	1.24
Cor 36-60	Mt. Hole	33	26	36 (An_{35})	1	1	1	0.5	4.25, 3.52, 3.64	3.8
†Cor 2	Dike in Temescal Wash	34	11	45 (An_{30})	6†	1	1	....	.....	1.73
Ra 106	Lake Wolford	38	2	51 (An_{28})	7**	....	2	....	.71, .87, 1.77	1.08
El 31	Aplite	....	....	.....	....	....	....	....	.....	.39
El 38-23	Aplite	....	....	.....	....	....	....	....	.....	.43
SLR 643	Aplite	....	....	.....	....	....	....	....	.....	2.69
Average of granodiorites based on rock outcrops										1.8

* Contains secondary epidote and muscovite.
† Biotite is altered to calcite, some secondary epidote.
** Contains secondary chlorite, epidote, muscovite.

LAKE WOLFORD GRANODIORITE

This unit is variable and is probably a complex. The specimen tested (Ra 106) represents a local, fine-grained, potash-poor variety. The mineral composition and activity are given in Table 4.

APLITES

Activity data for three aplites of granodiorite composition are given in Table 4. The activity of two of these is much lower than that of the granodiorites of about the same composition and for the third is about average for the granites.

GRANITES

Granites form a very small part of the batholith. The largest body occupies an area of about 15 square miles in the drainage basin of Roblar Creek, in the northern

part of the San Luis Rey quadrangle. A micropegmatite forms a small body a few miles northeast of Corona. Two granites, one fine-, and one coarse-grained, form Mt. Rubidoux near Riverside. Many aplite dikes with miarolitic cavities cut the Woodson Mountain granodiorite in the drainage of Coldwater Canyon, in the Corona quadrangle. The modes and activities of the granites are given in Table 5.

TABLE 5.—*Mineral composition and activity of granites*

Number	Formation	Quartz	Perthite	Plagioclase	Biotite	Hornblende	Opaque	Activity in alphas/mg./hr.	
								Individual determinations	Average
SLR'L 38.....	Roblar	41	50	6 (An_{21})	3	.....	0.3	.....	2.73
Cor 3.....	Micropegmatite	34	50	13 (An_{21})	1	.....	2	3.26, 2.65, 3.47	3.13
El 38-167.....	*Coarse of Mt. Rubidoux	35	57	4 (An_{23})	3	.....	....	.....	1.73
El 38-265.....	†Fine of Mt. Rubidoux	35	48	14 (An_{30})	3	.....	....	.....	2.23
Cor 36-91.....	Aplite Miarolitic	....	....	.....	....	.....	....	.....	1.86
Average based on rock outcrops.....									2.5

* Accessory apatite, sphene, zircon, allanite, and an iron-rich hypersthene.
† Accessory zircon, monazite, sphene, and allanite.

MISCELLANEOUS ROCKS

A quartz latite porphyry that cuts the Bonsall tonalite west of Winchester, in the Elsinore quadrangle, may be Tertiary in age. It (El.316) has an activity of 1.77 α/mg./hr.

A fine-grained granodiorite from the Santa Margarita Mountains (S.L.R.37) in the northern part of the San Luis Rey quadrangle is probably older than the batholith and younger than the Triassic sediments and Jurassic (?) volcanics, and hence is Jurassic (?); it has an activity of 2.21.

A specimen (S.L.R.1048) from a small body of granodiorite near El Saltro in the San Luis Rey quadrangle has an activity of 1.35.

CONCLUSIONS

The activities of 43 rocks from the batholith have been determined, and the data are plotted in Figure 2 against the position ($\frac{1}{3}$ $SiO_2 + K_2O - FeO - MgO - CaO$) on the variation diagram after Larsen (1938). The K_2O, SiO_2, and PbO of the rocks are also plotted. The average activity for the gabbros near the left border of the diagram is about 0.3, that of the tonalite is about 0.8, that of the granodiorite is about 1.4, and that for the granite is over 2.5.

The curves for activity, SiO_2, K_2O, and PbO slope in the same direction, and all four oxides are relatively low in the gabbros and increase progressively as the rocks approach granite. PbO follows K_2O closely as it is concentrated in the potash minerals, but activity follows K_2O only because both are concentrated in the residual

liquid as the activity is very low in the potash minerals and is concentrated in the accessory minerals—zircon, apatite, allanite, sphene, and monazite. The ratio of K_2O (in per cent) to activity (in α/mg./hr.) and of PbO (in parts per million) to activity are given in Table 6.

TABLE 6.—*Ratio of K_2O (in percentages) to activity (α/mg./hr.) and PbO (parts per million) to activity for rocks from gabbro to granite*

Rock	K_2O/A	PbO/A
Gabbro	1.0	15.0
Tonalite	2.0	18.0
Granodiorite	2.1	12.0
Granite	1.7	7.0

TABLE 7.—*Correlation of various constituents with relation to their failure to fit the variation curves*

	Lead high	Lead low	Activity high	Activity low
Other constituents check	5	1	3	.....
Activity high	.....	3	.....	.....
Activity low	.....	4	.....	.....
Activity low	2	.....	.....	.....
K_2O low	.....	1	.....	2
SiO_2 low	.....	.....	1	.....
SiO_2 high	.....	1	.....	.....
PbO low	.....	3	2	1
No PbO determination	.....	.....	1	.....
PbO low, K_2O low	.....	.....	.....	1
PbO high, K_2O low	.....	.....	.....	1

The activity of 11 out of 36 rocks falls more than 0.5 α/mg./hr. from the variation curve, and the PbO for 17 out of 30 rocks falls more than 5 parts per million off the variation curve. Table 7 correlates the failure to fit the variation curves for the various constituents.

The table indicates a slight tendency for erratic activity to be accompanied by erratic PbO.

Of the 12 erratic determinations for activity, 5 were made in triplicate, and one in duplicate. For each determination a sample from a separate hand specimen was used. The large number of erratic determinations may be in part due to imperfect sampling, but much of it probably represents actual failure of the activity to follow a simple law.

The Mt. Hole granodiorite has the highest activity; average of three determinations is 3.8. This rock fits the variation diagram fairly well, though the K_2O and PbO are slightly high. The rocks contain more allanite than the other rocks, and allanite is present in all specimens collected from this formation. The increased radioactivity is probably associated with the allanite.

The activity of the average rock of the batholith, considering the area underlain by the different rocks, is about 0.9 alphas per milligram per hour.

REFERENCES CITED

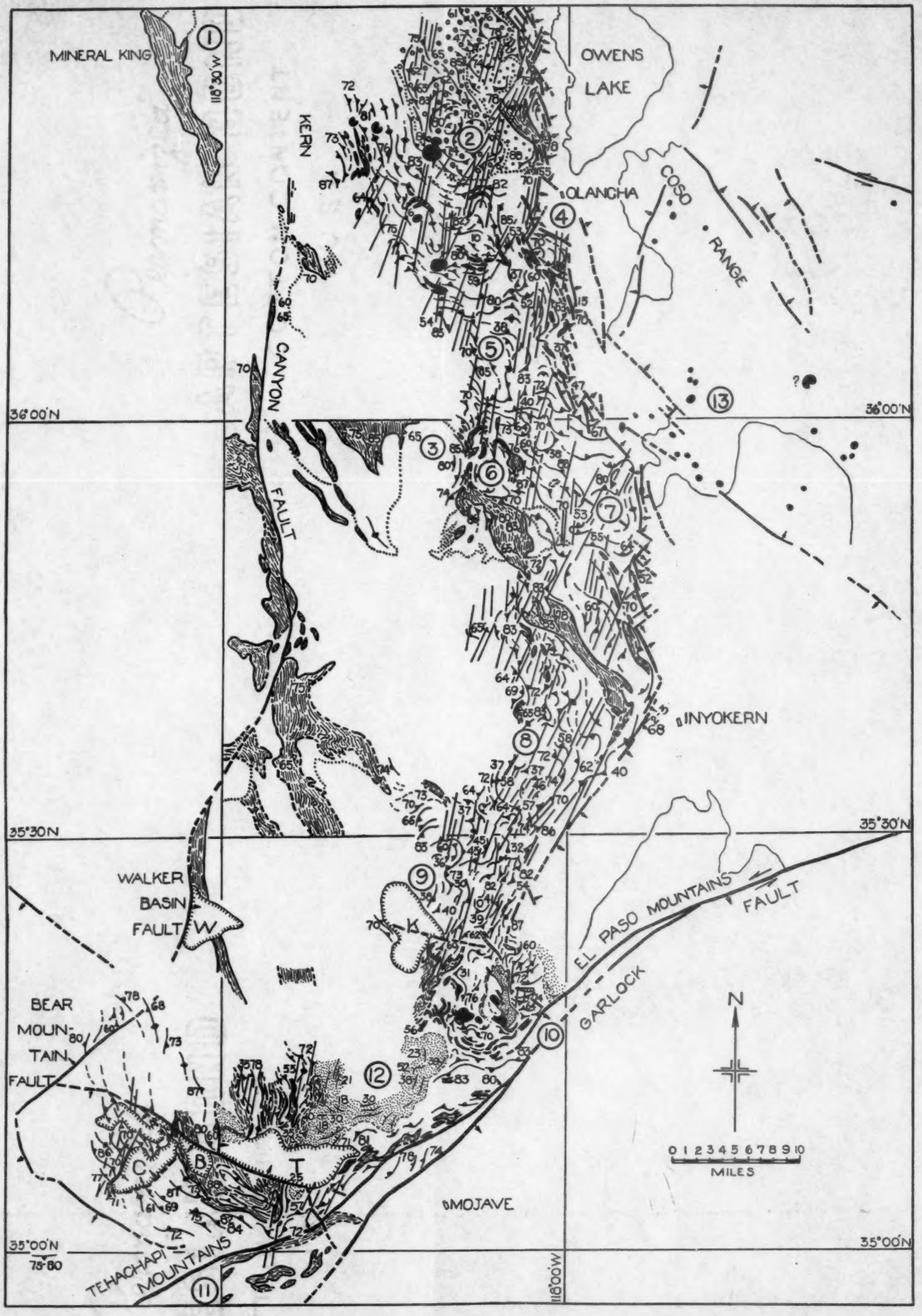
Keevil, N. B., Larsen, E. S., and Wank, F. J. (1944) *The distribution of helium and radioactivity in rocks*, Am. Jour. Sci., vol. 242.

Larsen, E. S. (1938) *Some new variation diagrams for groups of igneous rocks*, Jour. Geol., vol. 46, p. 506–520.

——— (in press) *The batholith and associated rocks of the Corona, Elsinore, and San Luis Rey quadrangles, Southern California; a sample from the Great Batholith of Southern and Lower California*, Geol. Soc. Am., Mem.

Miller, F. S. (1937) *Petrology of the San Marcos gabbro, Southern California*, Geol. Soc. Am., Bull., vol. 48, p. 1397–1426.

Geological Museum, Oxford Street, Cambridge, Mass; University of Toronto, Toronto, Canada
Manuscript Received by the Secretary of the Society, July 1, 1946
Project Grants 420/42, 381/44.



CRYSTALLINE ROCKS & STRUCTURES

- Cathedral Peak Granite.
- Eugranitic Qz Monzonite.
- Other Units of the Intrusive Series in the Sierra.
- Metamorphic Rocks.
- Same, in Ill-defined, Recrystallized, Injected Masses.
- Steep (>59°) Joints, N-NE Direction.
- Contacts Between Part-plutons.
- Contacts Between Composite Pluton and Wall Rocks.
- Planar Flow Structure.
- Same, Vertical.
- Cleavage and (or) Bedding.
- Same, Vertical.

TERTIARY-QUATERNARY ROCKS & STRUCTURES

- Tertiary Volcanic Spreads & Sediments.
- Tertiary Dikes.
- Tertiary Plugs & Volcanic Domes; Pleistocene & Recent Cinder Cones.
- Bedding in Tertiary Sediments.
- Fault, with Direction of Dip of Scarp.
- Same, with Dip of Plane and Pitch of Striae.
- Fault, with Horizontal Shift.
- Structural Depressions.
- W Walker Basin.
- K Kelso Valley.
- T Tehachapi Valley.
- B Brite Valley.
- C Cummings Valley.
- V Bear Valley.

STRUCTURE PLAN OF THE SOUTHERN SIERRA NEVADA, CALIFORNIA

Compiled from maps and papers by A. C. Lawson, A. Knopf, P. Thelan, W. J. Miller, R. W. Webb, E. C. Simpson, J. Murdoch, R. H. Hopper, and from original field work. Base from U. S. G. S. topographic maps of Olancha, Kernville, and Mojave quadrangles, and parts of Ballarat, Searles Lake, Kaweah, Caliente, Tejon, and Elizabeth Lake quadrangles. Numbers 1–13 indicate localities mentioned in text.

Ab
Int
Ac
Pr

Te

Di

Ref

Pla
1

I
ca
co
en
pr
Th
the

T
fro

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 58, PP. 495–504, 1 PL. JUNE 1947

STRUCTURE PLAN OF THE SOUTHERN SIERRA NEVADA, CALIFORNIA

BY EVANS B. MAYO

CONTENTS

	Page
Abstract	495
Introduction	495
Acknowledgments	496
Pre-Tertiary rocks and structures	496
General	496
Crystalline rocks	496
Structure elements	497
Flow and fracture pattern	497
General statement	497
Examples	497
Tertiary-Quaternary features	499
Tertiary volcanic spreads and sediments	499
Tertiary volcanic outlets	499
Faults	500
Structural depressions	500
Pleistocene and Recent volcanoes	501
Discussion and conclusions	501
General	501
Origin of the southern Sierra curve	501
Structural evolution	502
References cited	503

ILLUSTRATIONS

Plate	Facing page
1. Structure plan of the southern Sierra Nevada, California	495

ABSTRACT

In the southern Sierra Nevada schist remnants, flow layers, joints, faults, and volcanoes combine into a regional pattern that seems to have persisted throughout recorded geological history. From this pattern it is deduced that, toward the southern end of the Sierra, north-northeast and northeast structures gained control over the prevailing northwest structure and swung the trend from southeast to southwest. This swing, expressed in the present topography, had been accomplished by the time the pluton was emplaced, and probably long before.

INTRODUCTION

The eastern front of the northwest–southeast trending Sierra Nevada swings from southeast to southwest at the southern end of the range. It is known, of

course, that the Sierra ends southward at the Garlock fault (Pl. 1) and that this fault is, geologically, very young (Hulin, 1925, p. 63–64; Simpson, 1934, p. 403). Was the Sierra structure, at a very late stage of its history, abruptly chopped off; or is this new break an adjustment along the ancient structure?

The answer lies far back in the geologic history and cannot yet be given in final form. Data are at hand, however, to advance materially our understanding of the problem. A report on structures observed between Mt. Lyell and Mt. Whitney has been published (Mayo, 1941). The present preliminary paper is a summary and discussion of some of the structures between Mt. Whitney and the Tehachapi Mountains.

ACKNOWLEDGMENTS

The references and the explanation of Plate 1 show, however inadequately, the writer's indebtedness to other workers in this region. His field work was financed by a grant from the Penrose Bequest of The Geological Society of America. Richard H. Jahns made suggestions which improved both manuscript and map.

PRE-TERTIARY ROCKS AND STRUCTURES

GENERAL

It is convenient to separate the crystalline, pre-Tertiary rocks and their structures from the Tertiary-Quaternary-features. The crystalline rocks hold the record of Nevadan (Upper Jurassic) and possibly of earlier orogenies; the Tertiary-Quaternary features record the events that followed Nevadan orogeny and Cretaceous erosion.

CRYSTALLINE ROCKS

The oldest crystalline rocks are schists, crystalline limestones, impure quartzites, stretched conglomerates, and minor lenses of sheared meta-volcanics (Pl. 1). Most of these rocks have been assigned to the Paleozoic and correlated tentatively with the Calaveras formation of the western foothills of the Sierra (Miller and Webb, 1941, p. 352–353). It has been suggested, however (Simpson, 1934, p. 383), and locally proven (Durrell, 1940, p. 17), that some of the areas of metamorphic rock are Triassic. The metamorphic rocks now exist as roof pendants, or septa, in or between the intrusive units (part plutons) of the Sierra Nevada pluton.

The intrusive rocks of the composite Sierra Nevada pluton form a petrographic series that ranges from gabbro to granite. With local exceptions, the part-plutons were emplaced in order of increasing silica. Forerunners, named Summit gabbro by Miller and Webb (1941, p. 353–354), are the earliest intrusions. These gabbros, not shown on Plate 1, were followed by the Sacatar quartz diorite. Still later intrusions, comprising the bulk of the pluton, were mapped and described by Miller (1931, p. 344–351) who named these rocks the Isabella granodiorite. Isabella granodiorite seems to be a complex of several part-plutons. Among the latest intrusions in the northern part of the area (Pl. 1) is eugranitic quartz monzonite (Knopf, 1918, p. 63–65) and Cathedral Peak granite (Calkins, *in* Matthes, 1930, p. 126–127; Mayo, 1941, p. 1011), called porphyritic quartz monzonite by Knopf.

STRUCTURE ELEMENTS

The elements of pre-Tertiary age, shown on Plate 1, are as follows:

In the metamorphic rocks:

Bedding is locally destroyed by deformation and recrystallization and has been deformed into isoclinal or near-isoclinal folds with nearly vertical axial planes.

Cleavage approximately parallels axial planes of the folds, with some exceptions; therefore at most places it parallels bedding. Most structure symbols in metamorphics refer to cleavage, but measurements on bedding have the same symbols.

In the intrusions (E. Cloos, 1936, p. 371–403):

Flow layers, including planar schlieren and planar arrangements of inclusions and crystals, reveal the general outlines of the part-plutons and, supplemented by the flow lines (not shown on Pl. 1), portray the steep upwelling, as in thunderheads or puffs of smoke, of the magmas.

A few internal contacts, between part-plutons, have been mapped. External contacts, between the composite pluton and its walls (septa), or roof pendants, are indicated. At most places these contacts are steep, sharp, and concordant.

Regional joints traverse all crystalline rocks and contacts. Most of them follow one of four directions: (1) northwest, or Pacific Coast direction; (2) complementary to (1), the northeast direction; (3) nearly north–south, or north–northeast, Great Basin direction; (4) west–northwest direction, complementary to (3). Joints of direction (3) only are plotted on Plate 1, because it is necessary to avoid excessive detail, and in this area the relation of the nearly north–south joints to flow structure seems especially clear.

FLOW AND FRACTURE PATTERN

General statement.—The remnants of metamorphic rock (Pl. 1) define a sort of framework, or skeleton, that is filled in by the flow structures of the intrusions. In the southern Sierra Nevada, these remnants plainly reveal the Pacific Coast trend; they also show deviations from that trend, including the swing from southeast to southwest along the south–southeastern border of the range. Obviously, then, the curved front of the southern Sierra is structurally controlled; and, because Tertiary or later movements could not have rotated great strips of metamorphic rock that were embedded in solid granite, the control dates at least from the time of emplacement of the pluton.

The flow structures of the intrusions follow in general the pattern of the metamorphic rocks, thus revealing the control of intrusion by the structure of these closely folded rocks. In addition, the flow pattern discloses pronounced local swirls, or eddies, that mark the sites of especially vigorous upwelling. These swirls, and the trends of certain internal contacts, show significant relation to swarms of joints in the north–northeast, Great Basin, direction and in the northeast direction.

Examples.—The following examples illustrate the reactions of rising magmas to north–northeast, and northeast structures (abyssal fissures?) that traversed obliquely the Pacific Coast trend. The localities mentioned were local structural intersections.

(1) At the northern end of the Mineral King belt of metamorphic rocks is a small mass of tonalite (Knopf and Thelan, 1905, Pl. 30) elongated north–south.

(2) West of Owens Lake, swarms of north–northeast—south–southwest, and northeast—southwest joints slice obliquely southward into the Sierra Nevada. In the path of these fracture swarms are the northeasterly bulges at the northern end of the eugranitic quartz monzonite, northeast—trending, domelike swirls in flow layers in Cathedral Peak granite, and two prominent buckles, or noses, in flow layers south-southwest of the Cathedral Peak granite.

(3) The north–northeast—south–southwest fractures mentioned above trend southward toward a north-projecting prong of Isabella granodiorite (Miller and Webb, 1941, Pl. 2). This prong, in part, cuts obliquely across the Pacific Coast trend.

(4) A second zone of north–northeast—south–southwest joint swarms impinges upon the Sierra front south of Olancha. At this place, the front protrudes toward the north–northeast, and the resulting bulge is followed by flow layers.

(5) The second fracture zone, noted above, cuts obliquely southward into the Sierra and slices through the north–northeast bulging structure at (5).

(6) Still farther southward, a quartz diorite intrusion (Webb, 1938, p. 316; Miller and Webb, 1941, Pl. 2) partially disrupts a septum. This small intrusion appears to have been localized on the intersection of north–northeast fissures with the northwest- trending septum.

(7) Almost midway between Inyokern and Olancha, a third zone of north–northeast—south–southwest joints impinges on the Sierra front, and here again a bulge in the front is followed rather closely by the pattern of flow layers.

Hitherto, the effect of the north–northeast or northeast fissures seems to have been to cause crosscutting intrusions, or especially vigorous upwellings of magma on local intersections of the fissure swarms with northwest structures. On these intersections the upwelling magmas tended to follow the north–northeast or northeast fissures, so that flow layers and internal contacts locally follow one of these directions; but such "abnormal" trends of flow layers and contacts have been quite local.

Beyond Inyokern, however, the north–northeast—south–southwest direction dominates and, from (8) to Tehachapi Valley, is followed by flow layers and remnants of metamorphic rock. The dome of flow layers at (9) marks an intersection with northwest–southeast structures. North–northeast joints are legion in this area. Here as elsewhere, of course, the joints are not the fissures that fed upward the magmas. It is assumed, however, that these joints occupy approximately the sites of the abyssal channels. Kerr (1946, p. 10–19) has noted a relation between tungsten mineralization and the nearly north–south direction.

At (10) the northeast–southwest direction takes command, and it is followed by septa and flow layers to (11) and beyond. The Sierra ends, then, where the Pacific Coast direction yielded dominance, first to the north–northeast direction, then to the northeast direction.

TERTIARY-QUATERNARY FEATURES

TERTIARY VOLCANIC SPREADS AND SEDIMENTS

After Nevadan orogeny and Cretaceous erosion, the surface of Eocene time was slowly and intermittently uplifted, probably by a combination of warping and fracturing. This uplift was not uniform. Certain parts of the eroded surface, near the southern end of the present Sierra, sank, or lagged behind the general uplift. These relatively depressed areas became the sites of deposition of volcanic spreads (flows and pyroclasts) and sediments (Buwalda, 1934). The writer has little information on the sizes and shapes of these areas of Tertiary rocks, and the information on the geologic map of California (Jenkins, 1938) is not conclusive. From the incomplete data on Plate 1, however, it seems that positions and shapes of the Tertiary basins of deposition were determined by the pre-existing structural pattern. For example, the southeast border of the large body of Tertiary rocks at (12) follows the ancient northeast—southwest trend, and features seen on a brief visit to Kelso Valley (K) suggest that these Tertiary rocks extended north–northeast to the southern end of Kelso Valley. The small area of Tertiary rocks at (10) trends north–south, but details of its outline suggest some control by northwest fractures.

During or after deposition, the Tertiary rocks were folded. The folds in Tertiary rocks (12) are broad and open, at (10) they are closely appressed. As far as known, the resulting folds tend to parallel the borders of these Tertiary areas, but this relation requires further study. If true, it should throw light on the diverse southeast and southwest trends in the metamorphic rocks.

TERTIARY VOLCANIC OUTLETS

The most impressive area of Tertiary outlets is west of (10). Here, near the boundary between the Sierra Nevada and the Mojave Desert, north–northeast, northeast, and local northwest structures intersect. The pre-Tertiary structural pattern was very complicated, and the Tertiary deformation was especially intense. Granitic rocks of the pluton were locally reduced to crushed masses traversed by thousands of small, branching, folded shears. These crushed masses erode into badland forms. Tertiary dikes have filled folded shears, as well as later, straight fractures. Some of the Tertiary dikes were themselves sheared, and they appear to have been sharply folded. The several rhyolitic plugs in this area seemingly were forced viscously toward the then surface at the weakest places in the crushed crystalline basement. This small area merits detailed study.

Near and south–southwest of (2) are three latite plug domes of probable Tertiary age. The northernmost appears to have been erupted where a swarm of north–northeast joints crossed the Cathedral Peak granite contact. It is thought that the two more southern domes were protruded on intersections of north–northeast fissures with northwest flow layers, or shears.

At (13), perhaps 8 miles beyond the Sierra Nevada, is a group of rhyolitic domes, probably Tertiary. Their arrangement suggests control by north–northeast fissures, such as those that impinge upon the Sierra at (7), but the full number and pattern of these volcanic domes is not known.

FAULTS

Most of the faults shown (Pl. 1) last moved in Pleistocene or Recent time,[1] but it is not known when they first moved. Doubtless the ones shown are but a small portion of the total of faults in this area.

The faults follow the four previously mentioned regional joint directions. The Pacific Coast direction is followed by faults west of the northern end of Owens Lake, southwest of (13), north–northwest of Inyokern, 10 miles north of (10), and south of Tehachapi Valley. The northeast direction is followed by the Garlock and related faults. The north–northeast direction is followed by many small faults west of Owens Lake, by faults southeast of Owens Lake and southwest of Inyokern, and by the Walker Basin fault, west of Walker Basin. The west–northwest direction is followed by the Darwin tear fault, east–southeast of Owens Lake (accompanied by symbols indicating horizontal shift), by a large fault south of (13), by the fault that traverses Kelso Valley, and by faults that parallel the southwestern margin of Tehachapi Valley. The fault pattern, then, conforms with the much more ancient joint pattern; therefore the faults may either parallel or transect bedding, cleavage, contacts, and flow layers.

The Kern Canyon-Walker Basin-Bear Mountain chain of faults (Lawson, 1904; 1906a, p. 397–409; Webb, 1936) turns from due south to south–southwest to southwest, thereby reproducing with surprising fidelity the curve of the Southern Sierra front. Apparently this chain of faults traverses cleavage, flow layers, and other ancient structures throughout most of its length. The reason for the curved course of this chain of faults is not known; it seems to be unrelated to the ancient crystalline rock structure.

The so-called Sierra Nevada fault, along the eastern front of the Sierra, is a zone in which many faults of divers trends intersect. From Owens Lake to Inyokern the net result accomplished by these intersecting faults is to change the course of the Sierra front from southeast to south–southeast, in rather good conformity with the local trends of flow layers. Beyond Inyokern, north–northeast—south–southwest faults dominate, and the Sierra front follows the flow layers toward the south–southwest; faults and front follow the old structural grain. Likewise, the Garlock fault was not formed without regard for the most ancient structures. This fault also is approximately parallel to flow layers and schist remnants.

With very local exceptions, where intrusion was controlled by west–northwest fissures, the present west–northwest faults all traverse bedding, cleavage, contacts, and flow layers.

STRUCTURAL DEPRESSIONS

Near the southern end of the Sierra several large depressions result from faulting. At least one of these (Lawson, 1906b, p. 436) is known to have received Pleistocene sediments; all are receiving Recent sediments. These basins seem to be analogues of the Tertiary basins of deposition; they fit into the ancient pattern of flow and fracture structures.

[1] An important exception is the Kern Canyon fault (Webb, 1946). *See also* Buwalda (1915; 1920).

Walker Basin is a segment of a stream valley (Lawson, 1906a, p. 398–399) tilted westward and downward against the Walker Basin fault.

The faults that outline Kelso Valley are not known. The northern part of the valley has the Pacific Coast trend; the southern part trends south–southwest. The valley, then, is located on a turn in structure.

The eastern part of Tehachapi Valley is shaped by the northeast trend; the western part is oriented west–northwest. Brite Valley is elongated northwest but is cut off at the north by a west–northwest fault. Cummings Valley, as a whole, is elongated northeast, but a fault on its western side trends north–northeast. Bear Valley is elongated west–northwest, but its western end trends north–northeast. Bear Valley, therefore, was blocked out along two complementary directions of fracturing.

Beyond the Sierra front are many depressions whose shapes reflect the ancient structural pattern. For example, how similar is the triangular outline of Owens Lake, which occupies the deepest part of Owens Valley, to the flow pattern at (5)!

PLEISTOCENE AND RECENT VOLCANOES

The youngest volcanoes are well-preserved late Pleistocene or Recent basaltic cinder cones. Eroded basaltic outlets mark the sites of early Pleistocene or Pliocene eruptions. The investigation of the pattern of these volcanoes has hardly begun.

Southeast of (13), the cinder cones so far mapped seem to be aligned to northeast fissures. South of (13), the vents clearly are aligned to a west–northwest fault or zone of fissures. Eight miles west of (2) are two cinder cones[2] that probably lie on an east–west fissure. Both cones are breached toward the northeast, which suggests that the cones were erupted where northeast fissures intersected the east–west fissure.

DISCUSSION AND CONCLUSIONS

GENERAL

During the past few decades many writers, including Hans Cloos, F. P. Vickery, W. J. Miller, and Bailey Willis, have discussed the occurrence of clockwise horizontal shift along northwest fault zones in California. Some (Locke, Billingsley, and Mayo, 1940, p. 523–529) have suggested that the southern end of the Sierra Nevada was dragged into its present curve as a result of the shift. The writer agrees (1941, p. 1054–1058) that horizontal movements may have played an important part in the origin of some of the structural features of the Sierra, but he doubts that units as huge as the southern end of the Sierra Nevada were ever dragged around in the manner postulated. Existing data suggest that the curved structure grew on essentially its present plan.

ORIGIN OF THE SOUTHERN SIERRA CURVE

How did the southern Sierra structure grow? This structure is broadly curved. Examined more closely, however, the curve is seen to be composed of nearly straight

[2] Webb (1946, p. 369) mentions two additional outlets at this locality.

lines. As previously mentioned, from (8) to Tehachapi Valley the trend is south-southwest; from (10) to (11) the trend is southwest. Both of these trends are remarkably straight for long distances. If, at its southern end, the Sierra has been dragged by clockwise horizontal shift, the result is a huge drag fold; but why should a drag fold have this strange angular outline? Until an acceptable explanation is forthcoming, it seems best to discard the drag hypothesis.

When the pluton was emplaced, did the intrusions near the southern end of the Sierra Nevada, controlled by north–northeast and northeast fissures, elongate in these directions and force their metamorphosed walls out of the northwest–southeast trend into the north–northeast—south–southwest and northeast–southwest directions? Evidence presented elsewhere (Ernst Cloos, 1936, p. 360–363, 418–421; Mayo, 1941, p. 1070–1073) appears to limit the crowding aside of metamorphic rocks by intrusions, although the evidence of such crowding is locally very impressive. Moreover, if the metamorphic rocks in the southern Sierra Nevada have been so turned out of the northwest–southeast direction, is it not odd that they were forced aside along such straight fronts for so many miles? As already stated, the resulting trends are nearly straight; they do not bulge southeastward as one might expect them to do if the walls had been forced aside by aggressive intrusions. It seems, then, that the southern Sierra structure is not the result of either drag or forceful intrusion.

Consider Kelso Valley and the sediments that are now filling it. If the sides of this curved valley were forced together, would not the folded sediments assume a curved pattern, whose trends would change from southeast to southwest? If the area of Tertiary rocks at (12) extends northward to Kelso Valley, the open folds in these rocks probably do trend first south–southwest, then southwest. Field work is needed to test this possibility. By analogy, could the basins, or local troughs, on the floor of the geosyncline in which the metamorphic rocks were originally deposited have been curved or polygonal in outline? If so, the outlines of these basins could have been controlled by a fracture pattern like the one that exists here today. During the compressive phase of Nevadan, and perhaps of earlier, orogenies, the ancient sediments may have been folded against the curved, or angular, fracture-controlled basin margins; the resulting folds may have assumed the trends of those margins. If this explanation is correct, the intrusions at the southern end of the Sierra did not force the metamorphic rocks into the north–northeast—south–southwest and northeast–southwest directions; they merely invaded closely folded rocks that already had these trends.

STRUCTURAL EVOLUTION

The following tentative outline of the structural history is based on the above hypothesis. After the folding of the metamorphic rocks was essentially complete, the closely appressed folds, with curved or angular trends resembling the southern Sierra pattern of today, were invaded, step by step, by successive units of the pluton. This invasion was probably facilitated by gliding along northwest shears and by the resulting buckling of cleaved rocks (Mayo, 1941, p. 1073–1076). In this area (Pl. 1) horizontal motion seems to have opened pre-existing north–northeast fissures, and where these fissures intersected the northwest structures magma gushed upward

with especial vigor, as at localities (2) to (10). Where the trends of folds had changed, first to south–southwest, then to southwest, the trends of the intrusions and their flow structures changed likewise, because the feeding channels were the fissures that controlled the ancient basin margins. Shift and forceful emplacement added new details to the structural pattern, but they did not change its general features. After the pluton had consolidated, the regional joints were formed. These joints fit into the plan of the more ancient structures.

During the slow Tertiary upwarping certain small areas sank, or failed to rise. These areas became local basins of deposition. During compression, the resulting Tertiary rocks were folded. The Tertiary basins seem to fit into the older pattern, and the structure of area (12), for example, may be a miniature of the curve at the southern end of the Sierra. Although Tertiary rocks within the Sierra were folded during the Tertiary orogeny, more intense deformation occurred along the marginal zone between the Sierra Nevada and the Mojave Desert. Along this margin, the deformation was most severe where several structural trends converged, as near (10). At this place plugs of viscous rhyolite appear to have been squeezed upward through the crushed crystalline rocks.

The faults that result from vigorous Pleistocene-Recent uplift are distributed with close regard for the ancient pattern; therefore these young faults outline the curved Sierra structure and delimit the present Sierra Nevada. Within the Sierra, young tectonic depressions appear like sunken fragments of the structural mosaic.

Thus, the southern Sierra structural pattern, known to be at least as old as the Nevadan orogeny, has persisted and has found expression in the arrangements of Tertiary and Pleistocene structures. The ultimate origin of this structural pattern seems to retreat into ever more remote antiquity. An approach to this fundamental problem may have to include detailed studies of the structure of the Archean basement in neighboring regions. It will surely entail a study of broader areas within the Sierra Nevada.

REFERENCES CITED

Buwalda, J. P. (1915) *Structure of the southern Sierra Nevada* (Abstract), Geol. Soc. Am., Bull., vol. 26, p. 403.

——— (1920) *Fault system at the southern end of the Sierra Nevada, California* (Abstract), Geol. Soc. Am., Bull., vol. 31, p. 127.

——— (1934) *Tertiary tectonic activity in the Tehachapi region* (Abstract), Geol. Soc. Am., Pr. 1933, p. 312.

Cloos, Ernst (1936) *Der Sierra Nevada Pluton in Californien*, Neues Jahrb. Min., Geol., Palaeont., Beil.-Bd. 76, Abt. B., p. 355–450.

Cloos, Hans (1928) *Bau und Bewegung der Gebirge in Nordamerika Skandinavien und Mitteleuropa*, Fortschr. Geol., Palaeont., Bd. 7, Heft 21.

Durrell, Cordell (1940) *Metamorphism in the southern Sierra Nevada northeast of Visaia, California*. Univ. Calif. Pub., Bull. Dept. Geol. Sci., vol. 25, p. 1–118.

Hulin, C. D. (1925) *Geology and ore deposits of the Randsburg quadrangle, California*, Calif. State Div. Mines, Bull. 95.

Jenkins, O. P. (1938) *Geologic map of California*, Calif. State Div. Mines.

Kerr, P. F. (1946) *Tungsten Mineralization in the United States*, Geol. Soc. Am., Mem. 15.

Knopf, A. (1918) *A geologic reconnaissance of the Inyo Range and the eastern slope of the southern Sierra Nevada, California*, U. S. Geol. Survey, Prof. Paper 110.

Knopf, A. and Thelan, P. (1905) *Sketch of the geology of Mineral King, California*, Univ. Calif. Pub., Bull. Dept. Geol. Sci., vol. 4, p. 227–262.

Lawson, A. C. (1904) *The geomorphogeny of the upper Kern Basin*, Univ. Calif. Pub., Bull. Dept. Geol. Sci., vol. 3, p. 291–386.

——— (1906a) *The geomorphic features of the middle Kern*, Univ. Calif. Pub., Bull. Dept. Geol. Sci., vol. 4, p. 397–409.

——— (1906b) *The geomorphogeny of the Tehachapi Valley system*, Univ. Calif. Pub., Bull. Dept. Geol. Sci., vol. 4, p. 431–462.

Locke, A., Billingsley, P., and Mayo, E. B. (1940) *Sierra Nevada tectonic pattern*, Geol. Soc. Am. Bull., vol. 51, p. 513–540.

Mayo, E. B. (1941) *Deformation in the interval Mt. Lyell-Mt. Whitney, California*, Geol. Soc. Am. Bull., vol. 52, p. 1001–1084.

Matthes, F. E. (1930) *Geologic history of the Yosemite Valley*, U. S. Geol. Survey, Prof. Paper 160.

Miller, W. J. (1931) *Geologic sections across the southern Sierra Nevada of California*, Univ. Calif. Pub., Bull. Dept. Geol. Sci., vol. 20, p. 331–360.

——— (1940) *Some features of faulting in southern California*, Jour. Geol., vol. 20, p. 385–420.

——— and Webb, R. W. (1941) *Descriptive geology of the Kernville quadrangle, California*, Calif. State Min. Bur., State Mineral. Rept. 36, p. 343–378.

Murdoch, J. (1939) *Some garnet crystals from California*, Jour. Geol., vol. 47, p. 189–197.

Simpson, E. C. (1934) *Geology and mineral deposits of the Elizabeth Lake quadrangle, California*, Calif. State Min. Bur., State Mineral. Rept. 30, p. 371–416.

Vickery, F. P. (1925) *Structural dynamics of the Livermore region*, Jour. Geol., vol. 33, p. 608–628.

Webb, R. W. (1936) *Kern Canyon fault, southern Sierra Nevada*, Jour. Geol., vol. 44, p. 631–638.

——— (1938) *Relations between wall rocks and intrusives in the crystalline complex of the southern Sierra Nevada of California*, Jour. Geol., vol. 46, p. 310–320.

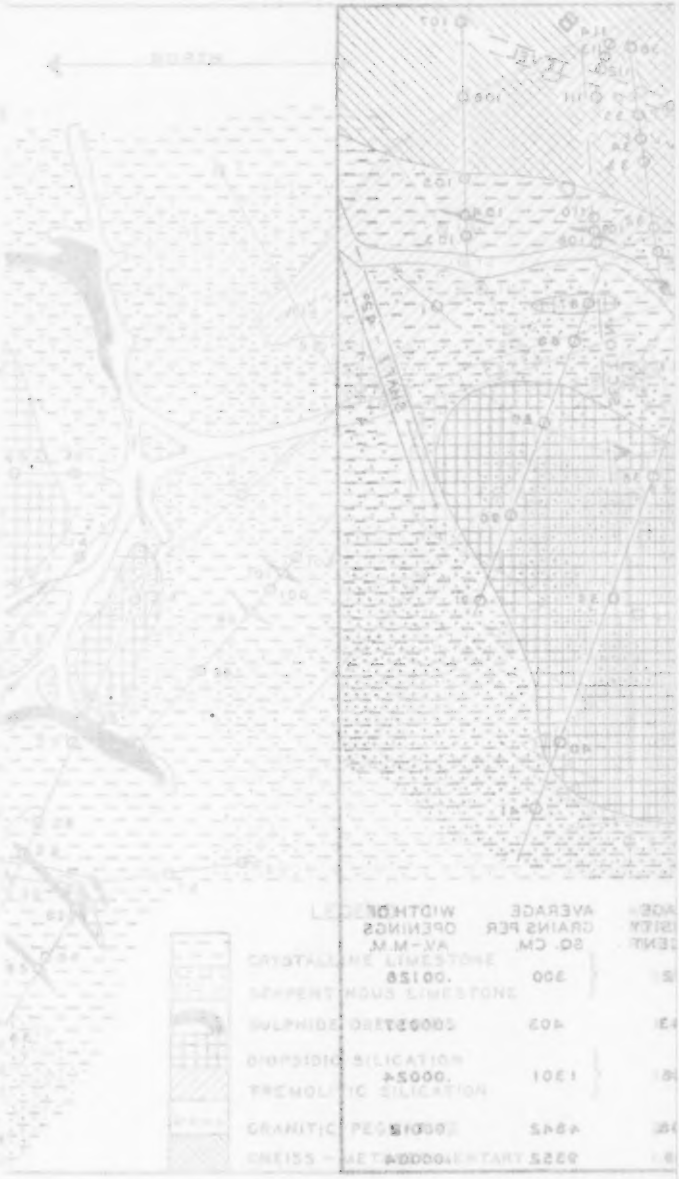
——— (1946) *Geomorphology of the middle Kern River Basin, southern Sierra Nevada, California*, Geol. Soc. Am., Bull., vol. 57, p. 355–382.

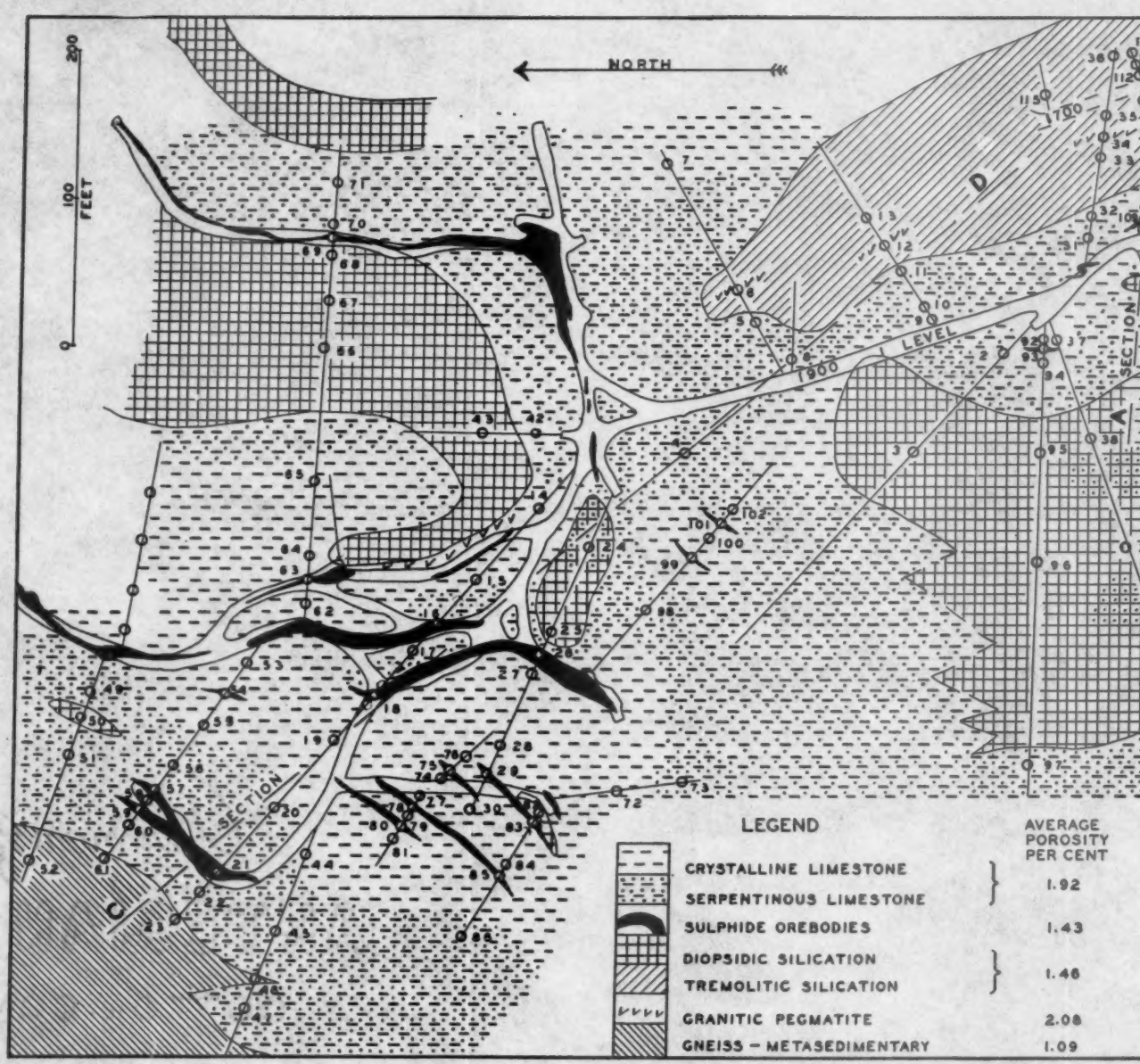
Willis, B. (1938) *San Andreas fault, California*, Jour. Geol., vol. 46, p. 793–827.

——— (1938) *San Andreas fault in southwest California*, Jour. Geol., vol. 46, p. 1017–1057.

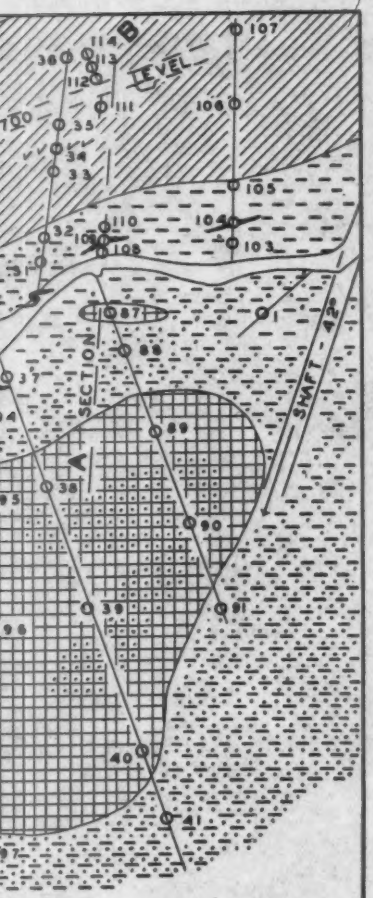
Kelowna Exploration Co., Hedley, British Columbia

Manuscript Received by the Secretary of the Society, June 17, 1946.
Project Grant 164/36.





GEOLOGY AND POROSITY DATA, 1900-FOOT LEVEL, EDWARDS MINE



ERAGE ROSITY R CENT	AVERAGE GRAINS PER SQ. CM.	WIDTH OF OPENINGS AV.-M.M.
1.92	300	.00128
1.43	403	.00057
1.46	1301	.00024
2.08	4842	.00012
1.09	9352	.00004

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 58, PP. 505-546, 10 PLS., 3 FIGS. JUNE 1947

POROSITY AND ORE DEPOSITION AT EDWARDS AND BALMAT, NEW YORK

BY JOHN S. BROWN

CONTENTS

	Page
Abstract	506
Acknowledgments	506
Background	507
Determination of porosity and size of openings	507
Localities chosen for study	510
Edwards mine data	511
General statement	511
Crystalline limestone	511
Serpentine limestone	511
Silicated limestone (diopsidic)	512
Silicated limestone (tremolitic)	513
Pegmatite	513
Gneiss	513
Zinc ore	513
General observations	514
Porosity data of crystalline limestone	514
Porosity data of silicated limestone	517
Porosity data of enclosing gneiss	517
Porosity data of pegmatite	518
Porosity data of zinc ore	518
Discussion of porosity data	520
Balmat mine data	521
Porosity data for unoxidized areas	521
General statement	521
Crystalline limestone	521
Silicated limestone (diopsidic)	521
Silicated limestone (tremolitic)	521
Gneiss	521
Diorite	521
Zinc ore	522
Oxidized areas	523
Porosity data for various types of rocks	523
Porosity data for zinc ore	525
Porosity data for miscellaneous types	525
Porosity data for oxidized areas	526
General statement	526
Crystalline and silicated limestone	527
Hematitic and chloritic wall rock	527
Zinc ore	528
Analysis of porosity data	531
Conclusions	535
References cited	540

ILLUSTRATIONS

Figure — Page
1. Apparatus used in determining porosity ... 508
2. Cross sections, 1500 to 1900-foot levels, Edwards Mine ... 512
3. Cross section, 600 to 700-foot level, Balmat Mine ... 522

Plate — Facing page
1. Geology and porosity data, 1900-foot level, Edwards Mine ... 505
2. Visual structures associated with ore occurrences ... 534
3. Visual structures associated with ore occurrences ... 535
4. Photomicrographs of typical rock and ore textures as related to grain counts ... 540
5. Photomicrographs of typical rock and ore textures as related to grain counts ... 541
6. Photomicrographs of typical rock and ore textures as related to grain counts ... 542
7. Photomicrographs of typical rock and ore textures as related to grain counts ... 543
8. Photomicrographs illustrating evidence for preore and postore deformation ... 544
9. Photomicrographs illustrating evidence for preore and postore deformation ... 545
10. Geology and porosity data, 1300-foot level, Balmat Mine ... 546

ABSTRACT

Many ore deposits are associated with channelways such as fault fissures, breccia zones, or porous formations, which afforded conduits obviously more favorable than the surrounding rocks. However, the zinc deposits of the Edwards-Balmat district, New York, replaced selectively certain bands or zones in an impure crystalline limestone unassisted by visible channels. Since the ore shoots extend more than 3000 feet without any great change in character, it is clear that the ore carrier operated for long distances in restricted channels with surprising uniformity, guided by features which, in many details, elude the human eye. The illumination of these controls by microscopic and other laboratory methods, in the hope that the results might shed some light on the nature of the ore fluid, has been the object of this investigation.

With respect to the nature of the controls, the author believes it is established that:

(1) Porosity was an important factor in determining the channels of deposition.

(2) The necessary degree and continuity of porosity were conditioned by microbrecciation which shortly preceded ore emplacement.

(3) This microbrecciation was concentrated, for physical reasons, in zones of impure limestone, roughly half carbonate and half silicate.

The openings utilized by the ore fluids were of microscopic dimensions, and probably nearer the lower than the upper limits usually regarded as capillary. The process of ore emplacement did not enlarge these openings but probably reduced them.

Paradoxically, porosity of the purer limestone types often found adjacent to ore bodies is consistently higher than that of the ore zones themselves and openings between grains are larger than those utilized by the ore fluids. The suggestion is advanced that under the temperature-pressure conditions of ore deposition this situation was reversed.

Much more research would be necessary to establish any definite conclusion as to the nature of the ore fluid. To the author, the suggestion of a gaseous medium seems attractive, but an inquiry into its possibilities is felt to be beyond the scope of this investigation.

ACKNOWLEDGMENTS

The Geological Society of America generously supported this research by a grant for the making of thin sections, the only important cash outlay. G. W. Bain of

Amherst College made the porosity determinations and supplied the basic data for calculating the size of openings according to methods he devised. He also made all the photomicrographs. Finally, the St. Joseph Lead Co. treated this research with tolerant approval and has consented to its publication.

BACKGROUND

The zinc deposits consist of approximately 50 per cent sulphide, chiefly sphalerite and pyrite, with minor galena, and replace certain zones in the metamorphosed pre-Cambrian Grenville limestone. The five or six ore shoots at Edwards range from 100 to 200 feet in strike length, from 2 to 20 feet or more in thickness, and extend with unbroken continuity, although with some changes in volume, to 2000 feet or more of vertical depth. At Balmat, the dimensions of ore shoots are larger, and other features differ only in details. More adequate general descriptions will be found in references cited at the end of this paper.

Two features have impressed the writer during his long experience as resident geologist.

(1) The vagueness of visual definition of the preferred ore channels.

(2) The pronounced absence of ore in the purer bands of limestone which, on chemical grounds, would seem to be most favorable for replacement. The writer (Brown, 1940) has established that the preferred host rock for ore, in this district, consists of an intimate mixture of carbonate and silicates, particularly diopside, in roughly even proportions. The ore avoids the intensely silicated masses and the purer carbonate areas. The natural presumption was that the preferred areas were most porous or permeable. The preliminary study of porosity, however (Brown, 1940), did not altogether confirm this assumption. This paper presents the results of a much more detailed study of the relations between rock types, porosity, and ore in these two mines.

DETERMINATION OF POROSITY AND SIZE OF OPENINGS

Porosity determinations in all cases were made on pieces of diamond-drill core, usually 2 to 3 inches in length and about three-quarters inch in diameter. Ordinary pieces of mine rock involve too much probability of error due to mechanical injury by blasting or otherwise. Although the possibility of injury in diamond drilling is not to be excluded entirely, it is believed to be unimportant in most cases, as indicated by the relative constancy of results on given types of rocks. Porosities were determined by Bain, using a method he devised originally for the study of marble in Vermont. Since no account of this method appears to have been published, the following description, based on notes made during a visit to Amherst, seems appropriate. Briefly, the apparatus consists of a system of bell jars connected by a rubber hose to a movable reservoir of mercury (Fig. 1). The bell jars are air-sealed and provided at the top with a glass measuring tube having a stop-cock. The specimen is first thoroughly dried in a desiccator to remove any moisture. It is placed in the bell jars with mercury above the level of the stop-cock, which is then closed; thereupon the mercury is lowered again until the bell jars are empty.

Any gas (air) in the specimen expands to fill the bell jars. The mercury is re-elevated compressing the gas into the measuring chamber, where it is read at 1 atmosphere as gauged by the height of the mercury reservoir. The volume of the specimen

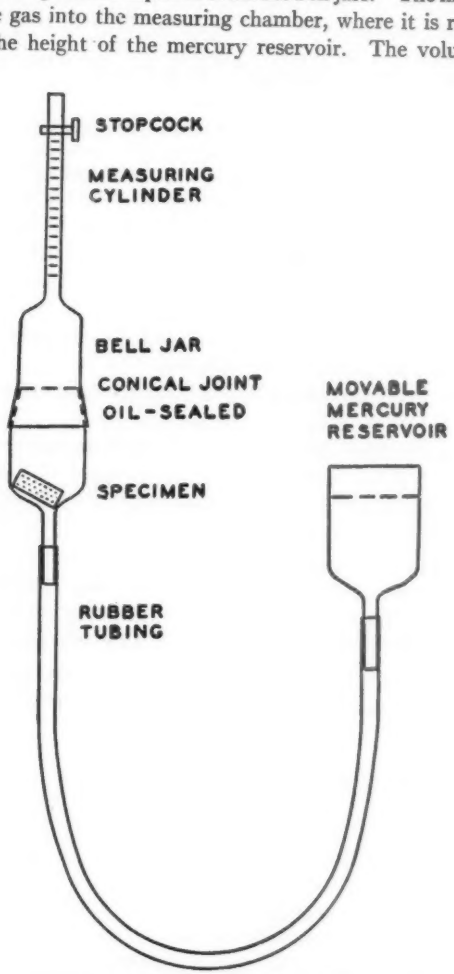


FIGURE 1.—*Apparatus used in determining porosity*

is determined by the volume of mercury it displaces when immersed, and the volume of gas in relation to the overall volume of the specimen measures the percentage of porosity. For rocks with small openings or low porosity the method is far more accurate and workable than any involving saturation by water or any known method that has been applied by geologists to the routine determination of porosity in crystalline rocks.

This method is not strictly rigid for several reasons.

(1) The desiccation process may not remove moisture completely.

(2) The bell-jar system may not be entirely free from leakage.

(3) Mercury has a vapor pressure of about .01 mm at room temperature.

(4) The expansion of air or other gas from the specimen, amounting generally to 0.3 to 0.5 cm^3, would reduce the vacuum to some degree, probably amounting roughly to 0.2 mm pressure.

(5) A minor fraction of the air would remain within the pores of the specimen at this low pressure, and an unknown fractional amount would adhere to the walls of the voids due to molecular adsorption.

In spite of these minor inaccuracies, with careful laboratory technique the vacuum should be on the order of 99 per cent complete, and the extraction of air from any voids likely to be effective for ore circulation should be considerably better than 90 per cent.

In devising his method Bain considered all these sources of error, checked them by various methods at Mellon Institute, and states in a personal communication that the error with respect to true porosity is less than 20 per cent.

Each porosity specimen was thin-sectioned at least once, and the sections were use to determine the average number of grains per square cm, using an ordinary petrographic microscope with micrometer eyepiece. Numerous lineal counts distributed over the area of the section were averaged and squared. From the count and the porosity determination a calculation of the size of openings is made according to a formula described by Bain (1936; 1941).

Bain's descriptions of the derivation of this formula are decidedly brief, and it has been subjected to some criticism (unpublished) in the course of preparation of this paper. The essentials of the Bain technique may be explained as follows:

(1) The number of grains in a unit area of crystalline rock is determined by standard microscopic counting methods in a thin section.

(2) The length of contact between these grains is actually measured for a unit area by usnig a measuring wheel on a photomicrograph.

(3) From these two sets of data a constant is determined for the particular type of rock under investigation, called the coefficient or irregularity (c). This constant is defined as $C = \frac{L}{G}$, where L is the length of contact and G is the number of grains in the unit area, and will be greater as the grains are more irregular and interlocking.

Knowing this constant for a particular thin section, or using an average constant for rocks of similar type, since it varies but little for such cases, the length of contact in a unit area can be computed. The average width of opening is then determined by dividing the volume porosity in a unit area by the area of contact. Naturally this average is merely an estimate of the general nature of the openings; actual voids will range from practically zero to perhaps 2 or 3 times the average width.

The foregoing method has been criticised by pointing out that, for a simple cubic lattice cut parallel to the cleavage planes, it is not applicable. In fact, in this special case, the relationship is easily computed as $A = \frac{3}{4} L$, not $L^{\frac{1}{2}}$. The similarity of equations leads to some confusion and a suggestion of error in the Bain formula. However, by constructing a cubic lattice and then sectioning it diagonally, it can

be shown that the simple formula, $A = \frac{3}{2} L$, no longer applies. In fact the result is variable, depending on the section cut, but L is increased, and the result becomes $A = \frac{8}{3} L \pm$.

The Bain formula was not intended to apply to simple geometric forms, however, but to complicated ones, and by similarly constructing the lattices pictured by Bain (1941, Figs. 1, 2) and cross-sectioning in various ways, the computations therein can be verified graphically. As stated by Bain, the formula is only an average, and individual slices will vary from the value given.

There still remains some question as to how applicable the formula may be to grain arrangements of the degree of irregularity found in natural rocks. Bain states (private communication) that the method was checked at Mellon Institute using a chemical process whereby a monomolecular film of gas was formed over each grain and that the results were never more than 50 per cent different from those obtained by the Bain formula.

Before utilizing the Bain formula, the author referred the matter of its validity to the Geological Department at Princeton University, which in turn had it checked over by the Mathematics Department. They expressed the opinion that Bain's formula was based on "the balancing of various fudge-factors" but for rocks of a similar degree of irregularity is approximately correct, providing the rocks have no pronounced linear or platy structures. It seems to the author from the experiments with wooden models that it is subject to some doubt also in the case of rocks with a simple geometrical grain arrangement, for which it is apt to overestimate the area and thus underestimate the width of opening.

In contrast to the Bain formula, it has been pointed out that metallurgists, particularly in the study of the grain size in steel, have used a method of estimation that yields considerably smaller values for grain-boundary area and corresponding y greater results for width of openings (*Metals Handbook*, 1939). A comparative tabulation, in fact, shows that the width of openings computed according to this method might range from 3 to 12 times as great as if computed by the Bain formula.

However, the shapes pictured and dealt with in this case are generally very regular, usually hexagonal in outline, and, therefore, much more closely resemble simple geometric lattices than natural rocks. Indeed, it is stated (*Metals Handbook*, 1939, p. 760) that this tabulation

> "shows the minimum possible interface area. The effective intergranular surface will be greater, particularly in the finer grain sizes, due to the undissolved carbide particles, and to irregularities in the true austenitic grain boundaries."

Obviously this system cannot be accepted as a reasonable method for the measurement of void widths in natural rocks but may be utilized for comparison as a means of estimating the ultimate range of possible deviation from the Bain formula.

LOCALITIES CHOSEN FOR STUDY

When this project was initiated, in 1939, there were available to the writer in the Edwards district two zinc mines—one at Edwards, N. Y., developed to 2100 feet of vertical depth and another at Balmat, N. Y., 10 miles away, 1300 feet deep. In both mines surface water had produced solution cavities and alteration effects to a

depth of more than 1000 feet. Since the chief object was to study the ore and its surrounding rocks as nearly as possible in their original condition at the time of ore deposition, it was necessary to choose areas well removed from the action of ground water. In order to be presentable in map form the data should be taken principally on a given mine level or levels. These levels should be reasonably thoroughly developed by mine openings, especially by diamond-drill holes, since drill cores supplied the best specimens for porosity determination. At Edwards these conditions were satisfactorily met by the 1900-foot level, one entirely free from surface water penetration and reasonably adequately explored. At Balmat the conditions were best met, although inadequately, by the 1300-foot level, the deepest in the mine, but one not fully explored and also distinctly affected at one end by the penetration of surface water with accompanying leaching and oxidizing effects. However, this level did afford an opportunity to compare areas of unmodified primary mineralization with others definitely subjected to secondary processes.

EDWARDS MINE DATA

GENERAL STATEMENT

Data for the Edwards mine are presented on a plan map of the 1900-foot level, (Pl. 1) and on some related cross sections (Fig. 2). On these are shown the rock classifications as developed by study underground and microscopically, based on all available mine openings and drill holes indicated in the illustrations. These also show the location of the specimens used for porosity determinations. Photomicrographs of typical textures and structures found in the more important types of rocks are shown (Pls. 4–9).

CRYSTALLINE LIMESTONE

Fifty per cent or more, of the rocks are crystalline limestone, as a rule more than 75 per cent carbonate, and rather coarsely crystalline. A limited number of chemical determinations have indicated that this ranges from calcite to dolomite, at Edwards tending toward the calcite end. The chief accompanying mineral is diopside, usually in small scattered grains. Mica and tremolite are occasionally present. Anhydrite, of uncertain origin, is common. Some serpentine and talc may be present. Normal crystalline limestone is white, soft, and usually glows momentarily if struck with a hammer in the dark. Some banding may be evident.

SERPENTINE LIMESTONE

Serpentine is abundant in much of the Edwards limestone, the more serpentinized areas are indicated on Plate 1. The average serpentine content is from 10 to 25 per cent. It occurs as spots of variable colors, usually green, but also brown and nearly colorless. Most of the serpentine in an alteration product of diopside, but it also extensively replaces carbonate. Where blocks or knots of silicates occur in the limestone, rims of serpentinous alteration are common. This limestone usually is rather distinctly banded.

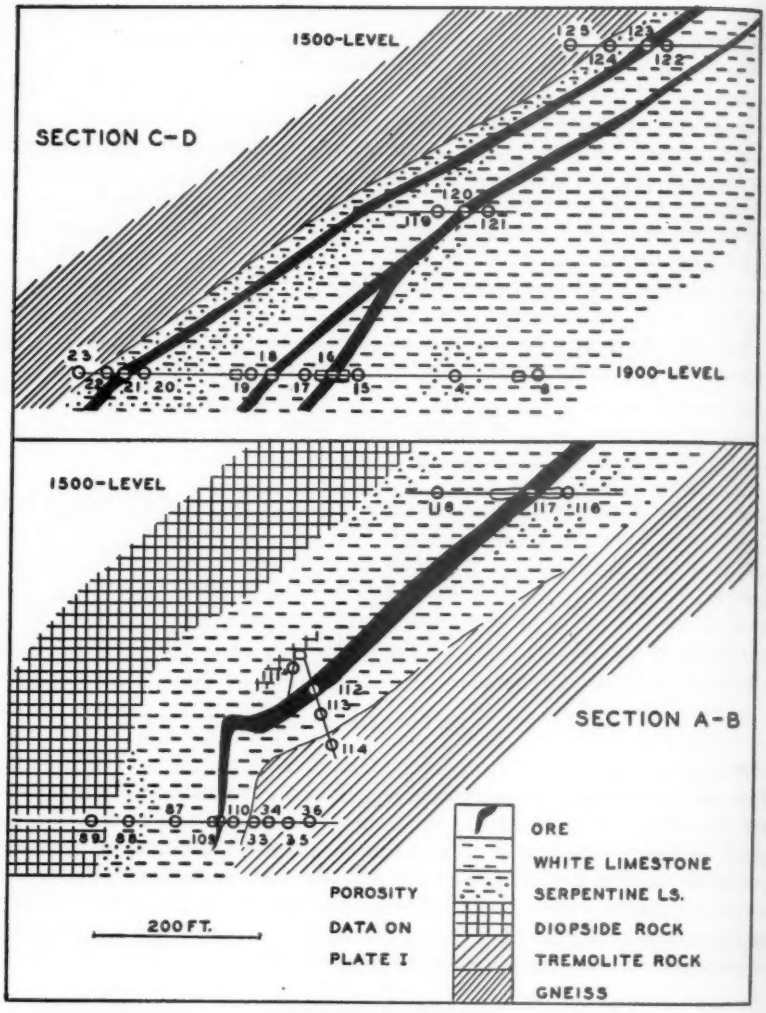


FIGURE 2.—*Cross sections, 1500 to 1900-foot levels, Edwards Mine*

SILICATED LIMESTONE (DIOPSIDIC)

Considerable areas in the Edwards mine consist of a highly silicated limestone containing 50 per cent or more diopside, in some cases little else. Although white (like the limestone) this rock is considerably finer-grained, harder, and may have a granular appearance. Some carbonate usually is present, and gradations exist that have to be classified arbitrarily. Tremolite, quartz, and anhydrite are present in minor amounts in some specimens. Serpentine is a fairly common alter-

ation product but in the finer diopside rock is much less abundant than in the limestone. Banding may be present but is usually less conspicuous than in the limestone. Healed fractures may be present.

SILICATED LIMESTONE (TREMOLITIC)

A rather large lenslike area of silicated rock contains coarse tremolite, ranging from clear to faintly green or brown, associated with considerable diopside, some clear mica, sporadic quartz, a good deal of carbonate, and spotty anhydrite, usually of a faintly pinkish tint. The rock is well banded, almost schistose, and contains irregular lenses of feldspathic pegmatite. Its visual differentiation is more pronounced than its statistical microscopic characteristics.

PEGMATITE

The Edwards mine contains numerous bands, lenses, and irregular masses of gray pegmatitic material consisting mainly of plagioclase feldspar and quartz, with occasional accessory sphene, apatite, anhydrite, marginal phlogopite and scattered sulphides. mainly pyrite and sphalerite. Sulphides are present only in the vicinity of ore bodies and evidently were introduced after the pegmatite had cooled considerably. Pegmatite masses seem to be lenticular vertically as well as laterally but are likely to recur in the same structural relations on successive levels. The amount of pegmatite increases with depth. Pegmatites were first recognized around the 1200-foot level in the mine. They are surrounded by erratic aureoles of silication. Their true significance and relations to the ore deposits are alone worthy of a study.

The pegmatite is of variable grain size. For the purposes of this paper the rock is probably of no great importance.

GNEISS

Surrounding the entire area of the Edwards mine in the form of a hook-shaped fold is a band of gneiss of considerable thickness which forms the practical limit of exploration, since it never contains ore. Only one small corner of this formation could be shown on Plate 1, but it surrounds the area of the map on three sides.

This gneiss is extremely fine-grained compared to the associated rocks and consists predominantly of feldspar, with considerable quartz, and various micaceous constituents such as sericite, biotite, and chlorite. The rock is evidently a metamorphosed sedimentary unit, considerably affected by igneous injection.

ZINC ORE

Edwards zinc ore consists roughly of about 50 per cent sulphides (in the specimens listed in this study nearly 60 per cent) of which approximately two-thirds is sphalerite, the rest chiefly pyrite. The gangue usually is high in diopside with some carbonate, more or less serpentine, and occasional barite, anhydrite, and accessories. The sulphides replaced mainly carbonate. The grain of the ore is usually rather coarse, and, owing to its optical uniformity, the sphalerite may appear fairly massive. The ore contains many prominent inclusions of unreplaced gangue, such as blocks and knots of silicates, especially diopside, and also at times of nearly pure crystalline

limestone. Thus it is often difficult to obtain specimens of ore which contain sufficient unreplaced gangue to be very instructive in thin section, except at the margins of ore bands or of included unreplaced fragments. There has been considerable postore fracturing of sulphides resulting in cracks filled with serpentine, talc, secondary carbonate, and gypsum which seam the sphalerite, pyrite, and gangue, but particularly the more massive ore.

Very commonly one wall of an ore body consists of exceptionally pure, coarsely crystalline limestone of the type previously described. In some cases both walls may be of this type, but commonly one wall is less pure, either a more or less serpentinous limestone or a more silicated type. These differences seem to be more evident macroscopically than microscopically and do not show markedly in the mapping, which is influenced principally by the microscopic character of specimens insofar as the distinction between serpentinous and nonserpentinous limestone is concerned.

The most significant feature of the ore probably is the strong visual suggestion of previous brecciation of the country rock. This is indicated by rounded disseminated fragments of what once were almost certainly more continuous silicate bands later stretched and torn in fragments by movement under conditions of plastic deformation. As a result nearly all evidence of fracturing was healed, and the harder fragments merge gradationally into the surrounding limestone, a large part of which was later replaced by ore leaving the silicate knots as conspicuous residuals.

Structurally, ore bodies are frequently associated with areas or bands of unusually complex folding or crumpling, and remnants of sharply flexed and folded bands are preserved at many places in the ore in striking attitudes.

GENERAL OBSERVATIONS

There are a number of exposures in the mine workings of mixed rocks consisting of highly silicated diopside rock in well-defined continuous bands or layers 1 to 6 inches thick, separated by softer bands of purer limestone usually of the serpentinous type. At places these show varying degrees of disturbance and dislocation with the softer limestone molded over the broken edges of elongated fragments of the silicate bands. These exposures evidently represent phases of the process by which the apparent vague breccia zones of the principal ore bodies were developed. In some cases there are even "breccias" of this sort which look like excellent replicas of ore zones without ore. Yet it should be clearly understood that none of these breccias contains any visible open spaces or fractures and that the porosities of any specimens taken from them, as very likely some of those included in Plate 1 have been, would all fall within the ranges of the associated rocks herein classified as either limestone or silicated limestone. The object of this study is to discover, if possible, some factor of difference in these various limestone or metamorphosed limestone products, sufficient to account for the localization of ore in certain preferred zones.

POROSITY DATA OF CRYSTALLINE LIMESTONE

For the 61 specimens having an average porosity of 1.92 per cent and grain count of 300 per square cm, the calculated width of the average opening between grains is .00128 mm, based on the Bain formula.

TABLE 1.—*Porosity data of crystalline limestone (including serpentinous limestone)*

Specimen No.	Carbonate (per cent)	Serpentine (per cent)	Porosity (per cent)	Grains/sq. cm
1	96		1.82	53
2	90		2.26	79
4	75	5	2.64	289
5	60		2.39	1764
7	80		2.48	183
8	98		1.60	73
9	55		1.90	1156
10	60	20	2.83	967
11	70	10	1.97	313
14	92		3.10	42
15	65		2.60	692
17	90		2.93	65
19	80		1.59	128
22	60	40	3.66	165
27	75		1.63	171
28	95		1.98	42
30	90		2.18	110
31	90		1.96	79
32	90	10	1.69	128
35	60		1.17	491
37	80		2.55	260
41	65	30	2.50	692
42	65		1.35	585
44	90		2.31	94
51	60	40	2.08	288
53	90		0.73	48
55	50		1.73	373
58	70	25	3.70	128
60	80	15	1.09	445
62	70		0.94	1065
64	85		1.92	165
65	65		2.29	840
70	75		1.66	770
71	90		1.53	94
72	80		1.02	165
73	65		1.08	65
74	50		2.59	692
76	85		1.23	135
77	75		1.69	260
79	90		1.10	188
81	75		2.35	110
84	65		1.87	313
86	55	40	.93	450
88	60	40	1.34	349
91	50	50	1.60	165
92	60	10	2.80	128
94	65	5	2.17	110
97	75	10	1.94	392
98	75	15	1.56	260
100	90		1.34	53
102	85	8	1.68	110
103	85		1.29	188
105	90		1.97	53

TABLE 1—*Concluded.*

Specimen No.	Carbonate (per cent)	Serpentine (per cent)	Porosity (per cent)	Grains/sq. cm
108	75		2.44	79
110	90		2.01	128
113	80		2.00	373
116	95		1.26	94
118	75		1.24	150
119	95		1.71	79
121	80		2.45	313
122	90		1.83	65
Total 61	*Average*.76		1.92	300
Average for 16 serpentinous specimens only.....			2.13	316
		Eliminated for various reasons		
20	75	20	4.55	Porosities too far out of line
45	60	35	5.30	Possible mechanical injuries
124	70		4.09	
48		90	1.19	Intricate serpentinization prevents grain count
49		50	1.71	
56		50	1.11	

The percentages of carbonate and serpentine are merely estimates on a volumetric basis made from the thin sections. Since serpentine has a fibrous texture virtually unresolvable by the microscope, no attempt has been made to count its constituent particles. Since most of the serpentine was derived from diopside and much of it forms aggregates, pseudomorphous after diopside, counts were based on the apparent number of original diopside grains. Where minor patches of serpentine replaced carbonate they were ignored. However, in a few cases, the replacement of carbonate was so intricate and extensive as to make it impossible to estimate the original number of grains before serpentinization.

At first a tabulation of serpentinous limestone separate from the nonserpentinous material was set up, but the differences were so slight as to indicate it had little value. One might expect serpentinization to introduce radical changes in porosity, but this seems not to be the case, particularly in the less advanced stages of alteration. Most of the specimens containing 40 per cent or more serpentine have rather lower than average porosity; yet No. 22 has a porosity of 3.66 per cent, and No. 45 (35 per cent serpentine) a porosity of 5.30 per cent. The latter is so high that it is rejected as mathematically unsound for inclusion. Altogether, it seems that serpentinization must have taken place without any significant change in porosity. Inasmuch as serpentine is at least largely, and probably entirely, of postore formation, and since the object here is to determine the size and nature of preore openings, the conclusion that serpentinization has introduced no marked causes of error makes the problem much simpler.

TABLE 2.—*Porosity data of silicated limestone*

Specimen No.	Diopside (per cent)	Notations	Porosity (per cent)	Grains/sq. cm
3	95		2.78	1600
13		50% Tremolite	2.24	1350
24	50	20% Serpentine	1.34	1354
25	25	40% Anhydrite	1.45	840
38	35	65% Quartz	2.53	2240
39	98		1.84	1764
43	40		1.80	666
47	40	20% Serpentine	.99	1600
50	60		1.05	485
66	50	50% Tremolite	1.43	997
67	65	35% Quartz	1.47	2766
68	50		1.23	692
82	80		1.62	750
87	95		.63	840
89	98		1.43	1156
90	95		1.70	2240
95	98		1.18	840
96	50	50% Quartz	1.22	1600
106	30	10% Mica	.94	1764
107		35% Tremolite 30% Quartz	.87	997
111	50		1.08	1764
114	85		1.35	313
Total....22	*Average*.....		1.46	1301
		Eliminated for various reasons		
33		Coarse tremolite	3.21	Porosity out of line too far
36			1.42	Strong alteration to talc
40			2.44	makes counting impossible

POROSITY DATA OF SILICATED LIMESTONE

A segregation of the diopside and tremolite types of silicated limestone in Table 2 was considered, but again the differences seemed insufficient and uninterpretable. At Edwards, silicated limestone is (essentially) a diopside rock, approximately 65 per cent of fine-grained diopside (ordinarily but little altered) in strong contrast to the minority percentage of diopside scattered through the purer limestone, which has suffered widespread serpentinization.

For the 22 specimens having an average porosity of 1.46 per cent and 1301 grains per square cm, the calculated average width of opening between grains is .00024 mm.

POROSITY DATA OF ENCLOSING GNEISS

Specimen 23 in Table 3 evidently is so near the gneiss-limestone contact that it is gradational and in porosity and grain count has strong affinities with the silicated

limestones. Hence it is rejected as not typical. The grain of the remaining rocks is so fine that the count is scarcely more than a crude estimate, highly inaccurate and almost certainly too low, indicating that the estimate of the size of openings is too large. The calculated average width of openings between grains is .00004 mm.

TABLE 3.—*Porosity data of enclosing gneiss*

Specimen No.	F = Feldspar Q = Quartz B = Biotite	Notations	Porosity (per cent)	Grains/sq. cm
46	F—Tr. Q—25 B—30	Considerable Diopside	1.34	6225
52	F—45 Q—5 B—10	Hornblende, Pyroxene	0.80	8465
61	F—50 Q—Tr. B—15	Sphene, Tourmaline	0.62	5417
125	F—5 Q—50 B—15	Considerable Diopside	1.60	17,300
Total..4	*Average*.....		1.09	9352
	Eliminated as out of line in porosity and composition			
23	F—35 Q—35 B—Tr.	Much Carbonate, some Pyroxene	2.14	1764

POROSITY DATA OF PEGMATITE

The specimens in Table 4 are insufficient, considering their variability, to supply a very good estimate of the characteristics of pegmatite, and the cores are so broken and brittle in some cases as to make it difficult to select satisfactory specimens for testing. The suggested average width of opening between grains by calculation is .00012 mm.

POROSITY DATA OF ZINC ORE

In specimen 59 (Table 5), the sulphides are strongly veined by later serpentine; in 69 by talc and carbonate veinlets; No. 109 is much shattered and healed by postore serpentine and barite; barite and calcite fill cracks in sulphides in 115; No. 123 is intensely shattered and healed by postore talc. The average porosity of these 5 specimens is 1.18 per cent and the grain count 350, based on the original grains before postore shattering. Experiments in counting the shattered fragments as separate grains (but not the thin intervening seams of later gangue) raised the grain

TABLE 4.—*Porosity data of pegmatite*

Specimen No.	F = Feldspar Q = Quartz	Notations	Porosity (per cent)	Grains/sq. cm
6	F—75 Q—20	Seams of talc	2.11	300
12	F—50 Q—50		2.55	8000
34	F—60 Q—40		1.58	6225
Average			2.08	4842

TABLE 5.—*Porosity data of zinc ore*

Specimen No.	Sulphides (per cent)	Notations	Porosity (per cent)	Grains/sq. cm.
16	60		2.73	400
18	70		1.78	100
26	75		1.91	146
29	85		2.91	216
54	40		1.36	260
57	70		1.16	146
59	70	*See* text	1.02	165
63	55		0.96	260
69	25	*See* text	0.88	840
75	65		1.16	400
78	60		0.52	392
80	55		0.96	313
83	80		1.54	102
85	60	Barite 5%	0.55	1600
93	35		1.94	165
99	40		1.86	165
101	45	Barite 15%	0.96	260
104	35	Barite 10%	0.97	2240
109	60	*See* text	0.91	475
112	65	Barite 10%	1.72	140
115	70	*See* text	1.53	188
117	65	Barite 10%	2.22	400
120	75		1.18	210
123	75	*See* text	1.58	79
Total....24	60	*Average*.....	1.43	403
		Eliminated as out of line too far		
21	60		4.30	Specimen very small and shattered

The calculated average width of openings is .00057 mm.

count from 50 to 200 per cent, on the average doubling it. Evidently postore changes did not alter the overall porosity greatly, but may have lowered it slightly.

Generally, ore specimens were more difficult to count satisfactorily than any of the limestone or altered limestone types, mainly because of the inability to distinguish clearly the probable constituent grains in sphalerite aggregates. However, the results seem reasonably consistent.

TABLE 6.—*Average characteristics of Edwards rock types*

Rock type	Porosity (per cent)	Grains/sq. cm	Width of openings in mm (Bain formula)
Crystalline limestone	1.92	300	.00128 mm
Ore	1.43	400	.00057 mm
Silicated limestone	1.46	1300	.00024 mm
Gneiss	1.09	9350	.00004 mm

DISCUSSION OF POROSITY DATA

Considered comparatively, the preceding tabulations are rather striking. The distinctions shown in Table 6, moreover, are notably clearcut. There are scarcely more than 2 specimens in the list of 61 crystalline limestones which, on the basis of grain count, seem more closely related to the silicated type. There is a fair number in which the percentage of diopside (including serpentine derived from it) indicates definite compositional gradation. Conversely, only a few of the 22 silicated limestone specimens suggest by low grain count or high carbonate content any pronounced gradation toward the limestone types. In neither list do any of them remotely approach the gneiss in point of grain count, although one specimen (No. 23) visually classified as gneiss had to be rejected from that group because of evident affinities to the silicated limestone type. The consistently low porosity of the gneisses is noteworthy, although it can be matched in occasional specimens from the other groups, especially the silicated limestone.

Zinc ore has a grain count slightly higher than the crystalline limestone and a porosity definitely lower, practically the same as that of the silicated limestone. Apparently the original host which the sulphides replaced was intermediate between these two types, as previously determined—a mixture with more silicates than the purer limestone and more carbonate than the highly silicated rock. Replacement by ore almost certainly has made the grain count lower than the original (*i.e.*, coarsened the grain) and also lowered the porosity.

One source of error in connection with the grain count and porosity data deserves evaluation. This is the presence in the constituent minerals in practically all the rock types of subsidiary openings, particularly cleavage cracks, in addition to the major contacts between mineral grains. Cleavage cracks or twinning planes are universal in the carbonate; cleavage cracks are abundant in diopside and sphalerite. In serpentine and talc there are, as previously stated, totally unresolvable subdivisions of constituent flakes or fibers. All these may contribute in an unknown degree to the determined porosity; on the other hand they may be so tight as to retain whatever gas adheres to their walls by virtue of adsorption. These factors, as well

as the probable tendency to undercount the grains rather than overcount, because of overlooking the smaller ones tend to render the tabulated estimate of the width of the main intergrain openings higher than the facts warrant.

On the other hand it could be argued that the Bain formula gives results too low (as compared, for instance, to the *Metals Handbook* system, 1939, p. 760) and that the true average width of opening may be considerably greater, possibly several times as great. This suggestion, if valid applies mainly to the purer crystalline limestone (Pl. 4), and even then only to a mild degree, considering its irregularity of grain as compared to any simple geometric pattern.

BALMAT MINE DATA

POROSITY DATA FOR UNOXIDIZED AREAS

General statement.—Data for the Balmat mine are presented on Plate 10, a plan map of the 1300-foot level, and on Figure 3, a cross section of an area above the 700-foot level. Rock types resemble those at Edwards in their broader features but differ in certain details.

Crystalline limestone.—This is a white limestone with some banding but usually not very conspicuous. The cleavage faces of the carbonate are notably large, many of them a quarter of an inch across. Serpentine is present but less abundant than at Edwards. The carbonate, according to a small number of analyses, is nearly pure dolomite. The chief impurity is a scattering of small diopside grains or of serpentine derived from diopside. Serpentinous limestone phases are present but much less widespread than at Edwards.

Silicated limestone (*diopsidic*).—A silicated limestone consisting predominantly of diopside or its derived serpentine is prominent at Balmat and either encloses most of the ore bodies or borders them on one wall. On the average, this rock contained originally around 70 per cent diopside, which may be now altered to serpentine (or less commonly talc) in almost any degree. The remainder is, or was, originally chiefly carbonate. The ordinary serpentinous diopside is considerably banded but in variable and erratic patterns. Brecciation of the flowage type, with diopside fragments enclosed in plastically molded carbonate, is fairly common. Due to serpentine, the diopside rock is usually quite greenish. The more intensely silicated areas may be massive and seamed by iregular tight fractures and cracks. A highly banded phase containing light-colored diopside and some quartz is found in places.

There is a diopsidic subtype which contains considerable mica, chiefly brown phlogopite, and but little serpentine. This rock is strongly banded, almost schistose.

Silicated limestone (*tremolite*).—A rock type widespread at Balmat, as contrasted to Edwards, consists of nearly pure fibrous tremolite, or of such tremolite pseudomorphically altered to talc. It forms lenses. Schistosity due to the fibrous character is pronounced. Some true flaky talc is included in these masses. Owing to its purity, there is little banding.

Gneiss.—Gneiss surrounds the Balmat mine as at Edwards but is so far away that it is not cut in the mine workings. One tongue of gneiss is encountered occasionally in drilling but does not show in the area of Plate 10.

Diorite.—No pegmatite has been found at Balmat, but a minor intrusive occurs

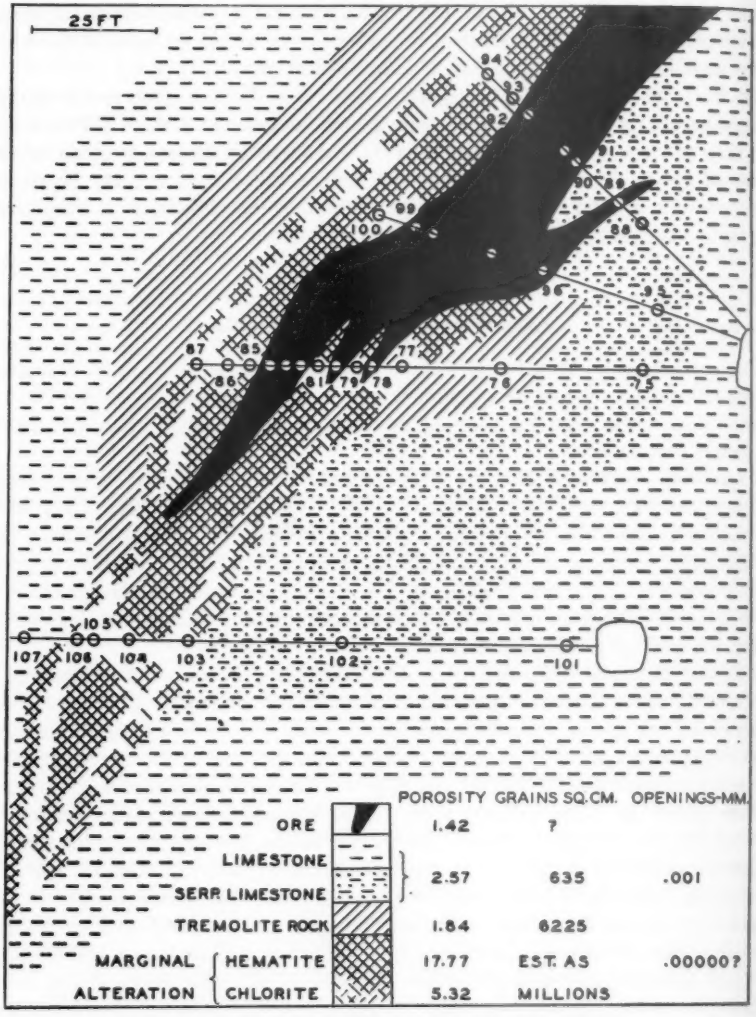


FIGURE 3.—*Cross section, 600 to 700 foot level, Balmat Mine*

as fine-grained black intrusive sheets, probably originally sills, now intricately folded, contorted, and broken into disconnected remnants, fragments of which occur at places in the ore bodies and elsewhere.

Zinc ore.—Zinc ore at Balmat, as at Edwards, contains roughly 50 per cent sulphides, more than half of which is pyrite and a small percentage galena. The gangue consists mainly of diopside, with a little carbonate, some quartz, and more or less talc and serpentine; the last two are later than the sulphides. Sulphides replaced mainly carbonate. Banding is pronounced at some places not at others, pyrite and

sphalerite form alternate bands. "Breccia ghosts"—unreplaced knots of highly silicated material, or occasionally of pure limestone—are common but less prominent than at Edwards. Structurally ore shoots tend to follow contacts between unlike wall rocks, particularly between limestone and diopside rock, or limestone and tremolite. Even within the area mapped as serpentinous diopside, narrow bands of purer limestone usually follow the ore on one wall or the other indicating that the ore body occupies a zone of compositional gradation.

TABLE 7.—*Porosity data-crystalline limestone*

Specimen No.	Carbonate (per cent)	Notations	Porosity (per cent)	Grains/sq. cm
3	65	Serpentine 25	2.11	94
12	95		1.66	128
20	90		1.19	154
22	95		2.13	128
24	85		3.04	313
32	97		1.42	94
34	80		1.52	210
38	98		1.02	128
40	97		2.49	165
Total.....9	89	*Average*.....	1.84	157
		Edwards comparison		
61			1.92	300

The calculated average width of openings between grains is .00197 mm.

Oxidized areas.—One feature prominent in the Balmat data does not occur at all in the level chosen for study at Edwards and was preserved only weakly in the now largely abandoned higher levels of that mine. This is the occurrence of strongly oxidized and secondarily altered bodies of ore and wall rock, especially pronounced at one end of the Balmat mine from the surface to the 700-foot-level and still present in appreciable strength on 1300. This alteration is attributed to the action of surface waters over a long interval at some undetermined period prior to the Pleistocene.

In these areas the walls of the ore bodies are intensely altered either to a soft aggregate containing a fairly high content of earthy-red hematite, or to greenish-black masses of talc and chlorite, the black and red types more or less intermixed and the intensity fading outward from the ore bodies in highly erratic fashion.

Within the ore bodies there is also a considerable development of hematite and chlorite, particularly along joints and fractures, and a highly irregular replacement of the primary sulphides by secondary sphalerite mixed with hematite and some magnetite. The details of this unique occurrence have been set forth elsewhere (Brown, 1936). A part of this study was devoted to an investigation of the porosity changes that accompanied this unusual alteration.

POROSITY DATA FOR VARIOUS TYPES OF ROCKS

It may be noted that No. 3 of Table 7, the only specimen containing appreciable serpentine, lies within an area wholly classified as serpentinous diopside rock. It

represents one of the numerous narrow bands of white crystalline limestone that traverse this area especially near the margins of ore masses but are not large enough to be mappable.

TABLE 8.—*Porosity data-silicated limestone, diopsidic*

Specimen No.	Diopside (per cent)	Notations	Porosity (per cent)	Grains/sq. cm
1	60	Mica—25	1.88	1764
2	50	Mica—20	1.70	997
5		Serp. 35	1.34	1156
6	90	Sulphides 10	1.38	1998
8	75		1.60	997
13	65	ZnS—20	1.18	585
14	97		0.84	313
15	90	Sulphides 10	1.09	1998
17	50	Serp. 20	1.05	1764
26	60	Serp. 20	1.17	1764
28	90		1.92	1156
30	40	Mica—20	1.87	840
36	60	Mica—15	1.57	1030
44	50	Con. Talc	1.08	3330
48	70		1.38	1520
50	60	Talc	0.86	3330
59	75		0.94	2475
67		Serp. 50	1.37	1350
69	60	Serp.	0.93	4675
72		Serp. 40	1.22	400
74		Serp. 40	1.27	1350
Total....21	*Average*.....		1.31	1657
		Edwards comparison		
22			1.46	1301
		Rejected-porosity out of line		
42		Talc—60 Sulphides 10	4.35	5417
52	95	Talc tremolitic	3.94	2766

The calculated average width of opening between grains is .00018 mm.

Grain counts (Table 8) on several of the accepted specimens are rather high, yet the average is not excessive as compared with Edwards. The prevalence of disseminated sulphides is quite different from the Edwards situation. Originally a separate tabulation of the micaceous facies was set up, but the differences seemed too slight to warrant its use. Average porosity for the four micaceous specimens is 1.75 per cent, and grain count 1160.

For the 22 specimens in Table 10 with average porosity of 1.36 per cent and 535 grains per square cm, the average width of intergrain opening is calculated at .00046 mm.

POROSITY DATA FOR ZINC ORE

In No. 7 sulphides are moderately shattered and healed by talc; pyrite in No. 16 is intensely cracked and seamed by talc; both pyrite and sphalerite in No. 18, 23, 25, 39, 51, 60, 70, and 71 are considerably cracked and healed by talc with occasional

TABLE 9.—*Porosity data, silicated limestone, tremolitic*

Specimen No.	Tremolite (per cent)	Notations	Porosity (per cent)	Grains/sq. cm
19	95		1.55	1640
35	75		0.91	2766
41	50	Quartz—50	1.48	740
46	95		1.08	3975
65	85		1.66	5417
Total.....5	*Average*.....		1.34	2908
		Rejected-intensely shattered		
29	95		1.18	
68	90		1.08	

All the tremolite is close to talc in composition, although identical with tremolite in structure. Numbers 29 and 68 (Table 9) are so intricately cross fractured that grain counting was difficult, and, with respect to original grain, meaningless.

The average width of intergrain openings is calculated at .00012 mm.

accompanying carbonate. In No. 62 some secondary sphalerite fills cracks in pyrite and older sphalerite.

Shattering of sulphides at Balmat is even more common than at Edwards, and grain counting to include fractured fragments would more than double the average count on the more shattered specimens. Yet the average porosity for the 10 specimens noted above is only 1.33 per cent, slightly under the general average.

POROSITY DATA FOR MISCELLANEOUS TYPES

In the diorites the feldspar is a medium calcic plagioclase. Considerable pyroxene has been metamorphosed to hornblende or biotite prior to ore deposition. Even though the rock may constitute irregular blocks within an ore body, it has completely resisted replacement except in its outer skin.

Specimens 37 and 61 of Table 11 are really intensely silicated limestone. Only No. 110 is a true gneiss comparable to the Edwards gneiss (Average porosity 1.09 per cent, grain count 9352). The location of No. 110 is beyond the limits of the map (Pl. 10).

This study of specimens from Balmat shows a remarkably close correlation with the results at Edwards. Crystalline limestone at Balmat is of distinctly coarser grain than at Edwards but still easily within the same range. The same relative porosity and grain count correspondence is shown by all the various types of rock. The ore at Balmat is of slightly finer average grain. The original rock replaced by

ore was definitely more silicated than at Edwards but still intermediate between the purer limestone and the intensely silicated varieties.

TABLE 10.—*Porosity data, zinc ore*

Specimen No.	Sulphides (per cent)	Notations	Porosity (per cent)	Grains/sq. cm
4	20		1.01	1000
7	24	*See* text	1.40	260
10	80		1.50	96
11	75		1.74	96
16	15	*See* text	1.57	1208
18	80	*See* text	1.43	246
21	70	Barite	1.43	313
23	50	Barite	0.77	692
25	40	*See* text	1.06	491
31	40		1.22	440
33	40		1.10	770
39	10	*See* text	1.20	1600
43	60		1.38	491
45	25		1.16	1998
47	40		1.75	424
49	60	Barite	1.16	158
51	60	*See* text	0.86	79
60	35	*See* text	1.67	146
62	80		1.33	128
66	75		1.74	384
70	60	*See* text	1.69	373
71	55	*See* text	1.63	373
Total....22	50	*Average*.....	1.36	535
		Edwards comparison		
21			1.43	403
		Rejected for various reasons		
9	25	Much Serpentine	3.24	313 Porosities too far out
27	40		2.97	110 of line
73	55	Much talc	1.55	Much talc prevents grain count

POROSITY DATA FOR OXIDIZED AREAS

General statement.—The principal data for this study are mapped in cross section in Figure 3. This represents a vertical east-west cross section of a portion of an important ore body which extends diagonally upward to its outcrop, with intense and generally increasing oxidation and alteration toward the surface, and downward with gradually diminishing effects, being the same ore shoot shown in the western part of Plate 10 on the 1300-level. The cross section near 600 feet of depth was chosen because of the reasonably complete picture afforded by the several drill holes at this

location. The data selected include both rocks clearly affected by the alteration and others not visibly modified.

Crystalline and silicated limestone.—The porosity of the limestone is appreciably higher than that of average limestone at the deeper level or at Edwards and may

TABLE 11.—*Porosity data, miscellaneous types*

Specimen No.	Composition	Notations	Porosity (per cent)	Grains/sq. cm
		DIORITE		
58	Feldspar 60 Pyroxene 30	Biotite 10	1.00	75000
108	Feldspar 50 Hornblende 30	Biotite 15	0.90	3600
109	Feldspar 60 Pyroxene 20	Biotite 20	1.00	25000
Total.....3	*Average*.....		0.97	34500
The calculated width of openings is .000013 mm				
		GNEISS		
37	Feldspar 70 Diopside 10	Phlogopite 15	1.82	8000
61	Quartz and Feldspar		1.97	70000
110	Quartz and Feldspar 60	Biotite 15 Hornblende 15	0.96	40000
	Average.....		1.58	39333

imply slight leaching. However, it may merely represent a concentration of specimens in a small locality of above normal porosity. The grain-count average is distinctly high, overweighted by the one fine-grained specimen, No. 75. Without this the average would be only 406. Including No. 75, the calculated width of openings is .00098 mm; without it, .0014 mm.

The one specimen of tremolite rock, not visibly altered, shows moderately high porosity for its type. There is no diopsidic silicated material in the area of Figure 3.

Hematitic and chloritic wall rock.—Here we have something new and startling! The soluble carbonate content of this wall rock has been removed almost completely, leaving only a skeleton of less soluble residuals (tremolite, barite, garnet) and a mass of chemical reconstitutions (talc, chlorite) and substitutions (hematite, chlorite, in part). With these changes porosity has been increased about 10 times, and grain size apparently has been reduced on the order of thousands of times. Yet in spite

of the tremendously increased porosity, if we allow for the apparent increase in grain count, the actual size of openings appears to have been reduced. Thus, estimating

TABLE 12.—*Crystalline limestone not visibly altered*

Specimen No.	Carbonate (per cent)	Notations	Porosity (per cent)	Grams/sq. cm
75	60	Serp. 20	2.00	1552
95	90		2.62	245
101	90		3.41	313
102	65	Talc 30	2.70	692
107	75	Talc 10	2.13	373
Total.....5	76	*Average*.....	2.57	635
		Rejected—Grain count impossible		
88	50	Talc 35 Serp. 15	1.67	Too much talc and serpentine
		Silicated limestone, tremolitic		
76		Tremolite 50	1.84	6225

TABLE 13.—*Hematitic wall rock-alteration intense*

Specimen No.	Composition	Porosity (per cent)	Grains/sq. cm
77	Talc and hematite	16.00	Count impossible, estimated to be in millions
79	Talc-chlorite-hematite	22.20	
93	Tremolite-hematite-chlorite	21.70	
105	Barite-talc-hematite	8.95	
106	Talc-hematite	20.00	
Total.....5	*Average*.....	17.77	
	1300-Level Comparison		
63	Carbonate 50, Diopside 40, Talc-hematite	4.22	2766

the average grain count at 4,000,000 per square cm, and using an average porosity of 17.77 per cent, the average width of opening would be .000007 mm.

As with the hematite type of alteration, the same general observations hold true in somewhat less degree. The chlorite-talc alteration is merely the first stage in the ultimate passage to the hematite type, the talc-chlorite type being replaced more and more by hematite.

Zinc ore.—In a preliminary study of porosities at Balmat a tentative suggestion was advanced, based on only one determination, that secondary alteration of the ore had caused sealing of the openings and a decrease in porosity (Brown, 1940). It now appears that this conclusion was based on inadequate data. No very definite

TABLE 14.—*Chloritic wall rock, alteration strong*

Specimen No.	Composition Notations	Porosity (per cent)	Grains/sq. cm
81	Tremolite—25 Barite—25 Talc-chlorite	2.17	Estimated
85	Carbonate—5 Chlorite—5 Talc—90	3.67	
86	Tremolite—40 Talc-chlorite—40 Hematite—10	8.99	Many
87	Tremolite—75 Talc-chlorite—25	3.31	Millions
94	Tremolite—25 Carbonate—60	3.44	
100	Tremolite Carbonate Chlorite	5.72	
103	Tremolite—70 Chlorite—25 Hematite—Tr.	7.32	
104	Willemite—65 Chlorite—50 Hematite—5	9.00	
Total.....8	*Average*.....	5.45	
	1300-Level Comparison (Plate 10)		
54	Talc-chlorite—80	5.08	
56	Tremolite—15 Talc—70 Hematite—10	12.00	
57	Tremolite—60 Talc-chlorite—35 Hematite—Tr.	9.70	
Total.....3	*Average*.....	8.93	

tendency is discernible in the preceding tabulation, and the conclusion seems to be that no pronounced unidirectional change has occurred in the ore body—in marked contrast to the effects on its walls. Total average porosity of the above 16 speci-

mens is 1.40 per cent, almost exactly the same as for primary ore at both Balmat and Edwards.

Significant changes have occurred in grain count so that all rocks in the oxidized

TABLE 15.—*Zinc ore*

Specimen No.	Sulphides (per cent)		Area of complete alteration	Porosity (per cent)	Grains/sq. cm
	Primary	Secondary			
Visibly oxidized and secondarily altered					
78	35	30	65	2.42	Impossible
80	50	25	50	1.17	"
82	65	25	35	1.75	"
89	65	10	20	2.05	"
92	35	30	65	1.04	"
99	42	20	55	2.33	"
Total.....6	*Average*..49	23	50	1.69	"
Oxidation and alteration visible only in thin section					
83	60	25	25	2.08	Impossible
84	80	10	15	0.70	"
90	93	2	Tr.	1.26	"
91	60	5	10	0.94	"
96	75	15	20	0.90	"
97	80	18	20	0.69	"
98	80	5	Tr.	1.10	"
Total.....7	*Average*..75	11	14	1.09	"
1300-level comparison (Plate 10)					
53	10	40	85	0.78	Estimated 284,000
55	35	25	50	1.90	Impossible
64	2	82	90	1.88	"
Total.....3	*Average*..16	49	75	1.52	"

area are exceedingly fine-grained. Rough estimates suggest that the grain count of sulphide areas would be measured in hundreds of thousands per square cm, reducing the average width of opening to perhaps .000005 mm.

The suggestion in Table 15 that the 1300-level is more completely altered than the higher area is misleading because of the small number of specimens represented and the more limited area in which they are available on that level. Secondary sulphides, in proportion to hematite and chlorite, are more abundant in the 1300-level altered area than at higher levels, a natural change with depth in a zone of supergene oxidation and enrichment.

ANALYSIS OF POROSITY DATA

With respect to the main problem, the nature of primary ore solutions, and the reasons for their localization, certain deductions seem soundly established, and the conclusions are amply corroborated by the data from both Edwards and Balmat.

Broadly, surrounding each mine, for the most part beyond the limits of the detailed maps presented herein, are great areas of highly altered metasedimentary gneisses which are completely inhospitable to zinc ore. These formations are represented by comparatively few, but very consistent, porosity determinations. This rock has a porosity of about 1 per cent, a grain count around 10,000 per square cm or more, and openings, therefore, calculated by the Bain formula as averaging .00004 mm, or less; in any case far below a micron (.001 mm) in width. Structural considerations indicate that these rocks acted as traps confining the ore carrier to tightly enclosed bodies of Grenville limestone. The gneisses were figuratively as impervious to the ore-bearing medium as steel. The ore-bearing formation, the Grenville limestone, is divisible broadly into two types:

(1) Comparatively pure unsilicated dolomitic limestone;

(2) Highly silicated and altered derivatives of this formation consisting mainly of diopside or tremolite.

The first has a porosity averaging almost 2 per cent, a texture expressed by counts of a very few hundred grains per square cm, and average openings calculable as .001 to .002 mm in width. (Even rejecting the Bain formula, the possible width could scarcely exceed .01 mm.) The silicated rocks have a somewhat smaller porosity averaging about 1.4 per cent, a grain count slightly above 1000 per square cm or at most a few thousands, and average openings estimable by the Bain formula at .0002 mm in width. Compared to the bounding gneisses, these rocks are exceedingly porous, and this difference apparently rendered them preferred channels for the passage of magmatic emanations.

In spite of their comparatively high porosity and wide intergrain spaces, ore is not universal in either of these two types of rock, indeed is seldom found in the purer examples of either type. Instead, ore was deposited in narrow and very restricted channelways mainly along particular bands which consisted, before replacement by ore, of a mixture of the two types, an intimate mixture of their constitutent minerals, particularly carbonate and diopside. These bands at Edwards are usually enclosed on both sides by limestone. At Balmat they usually are enclosed on either side by the more silicated diopsidic alteration of limestone. At both mines particularly at Balmat, ore was formed also on the marginal contact between masses of the silicated limestone (with diopside or tremolite) and the purer limestone. The ore zones at both mines are characterized structurally by vague but definite evidences of brecciation and shearing. However, visible cracks or cavities were seldom present and never of more than very local occurrence.

From its gradational habits and composition, the porosity of this host to ore must have been originally intermediate between the two more common types, that is around 1.65 per cent porosity, slightly below 1000 in grain count, with openings probably on the order of .00035 mm in average calculated width. At present the ore

still lies somewhat intermediate between the two main wall-rock types (1.40 per cent porosity, 400–500 grains per square cm, .0005 mm openings). It is reasonable to assume that the porosity has been reduced, perhaps by ore deposition and definitely by later end-stage changes, particularly the formation of talc and serpentine. The grain count also has been diminished by the deposition of sphalerite and pyrite in grains larger than those of the original host. The width of openings apparently has not changed in any pronounced degree.

Low porosity and especially small openings most probably rendered gneiss an unfavorable channelway for ore migration; likewise relatively low porosity and small openings rather clearly contributed to render silicated limestone (diopside rock or tremolite rock) unfavorable. It is clear on structural grounds in the mines that these rocks commonly acted in the conventionally accepted sense of dams or barriers guiding the movement of the ore medium.

There remains one anomaly deserving serious examination: Why did the ore carrier so sedulously avoid the purer limestone, a rock chemically ideal for replacement and having, at least as we now determine it, the greatest porosity and distinctly the largest openings of any of the rocks in the region?

Two possible explanations are suggested. One of these is predicated on the fact that we are now measuring porosities at no pressure and at ordinary surface temperatures, whereas the ore was deposited at a depth of thousands of feet under high rock pressure, and at undoubtedly elevated temperatures. The other is based on structural evidence both visual and microscopic within the ore itself. The two possibilities are:

(1) Under conditions of higher heat and pressure the relative porosities of the ore host and the bounding limestone may have been reversed.

(2) Although the porosity of pure limestone is high, it may not represent connected porosity available for the passage of an ore medium but may consist of isolated, comparatively sealed, and discontinuous openings. On the contrary, the ore host may have had slightly less porosity but better continuity of openings, a view distinctly supported by the structural evidence.

As to the first possibility some light is shed by the data in Table 16.

Data for dolomite unfortunately are not given, so it will have to be assumed that the characteristics of calcite apply in some measure. If each mineral grain would expand under increased temperature according to Table 16, at the expense of the intergrain pore spaces, then probably at the temperature of ore deposition a large measure of the present porosity of our ore-bearing formation was nonexistent. However, this is almost certainly only partially true and would be modified by increased pressure tending to reduce the specific volume of the mineral, as discussed later.

The variability of expansion of calcite is remarkable and indicates that if ore had been deposited at a temperature of 600° C., and the limestone was well oriented with most of its crystals parallel, the present high porosity of this rock would have been reduced almost to zero. That such a condition may well have applied is suggested by the common occurrence in the ore of comparatively thin bands of nearly pure limestone (1 to 6 inches thick), or of included blocks of such material, entirely unreplaced. It seems hardly possible that these small areas of gangue could have re-

sisted replacement if they had had anything like their present porosity at the time of deposition.

The unidirectional increases of volume for diopside with increased temperature would render highly silicated areas even less porous than now. The most favorable situation for the preservation of porosity should occur in pure limestone of hetero-

TABLE 16.—*Thermal expansion of calcite and diopside*
(Birch, 1942, p. 32)
Expressed in per cent based on 20°C. as unity

Temperature °C.	100°	200°	400°	600°	800°	1000°
Calcite ∥ c	.17	.45	1.07	1.80		
Calcite ⊥ c	−.05	−.13	−.24	−.33		
Volume	.08	.21	.60	1.14		
Diopside ⊥ 100	.03	.08	.20	.33	.47	.62
Diopside ⊥ 010	.10	.25	.57	.90	1.27	1.67
Diopside ∥ c	.02	.08	.18	.30	.43	.57
Volume	.15	.41	.95	1.53	2.17	2.86

geneous orientation; but the most favorable situation for the existence of heterogeneous orientation probably should be in zones of mixed diopside and carbonate, especially where these were affected by mechanical brecciation and disorganization, perhaps an important factor favoring the vague breccia zones in which the ore occurs.

The effect of high pressure at depth might offset in some degree, though probably only fractionally, the loss of porosity due to expansion under heat, since there should be a decrease in volume of individual grains (therefore leaving more intergrain space) with increase of pressure.

Data in *International critical tables* (1928, vol. 3, p. 50) and the *Handbook of physical constants* (Birch, 1942, p. 51, 54, 58) indicate that the compressibility of calcite at fixed temperatures is nearly a straight-line function up to more than 15,000 atmospheres (equivalent roughly to 30 miles in depth) and that the loss of volume is .66 per cent at 5000 atmospheres or 2 per cent at 15,000. For dolomite the reduction is a trifle less. For diopside the corresponding figures are .53 per cent and 1.60 per cent. The change in compressibility with variations in temperature is slight. On this basis, at 10 miles of depth the shrinkage in volume of crystals under pressure would counterbalance approximately the expansion due to 200° C. or at 30 miles of depth that due to 600° C., so that perhaps the porosities under these conditions might remain little changed.

Continuity of channelways due to brecciation may have been a more important factor than their actual size. There are two phases of geologic evidence, *e.g.* (1) macroscopic underground evidence, and (2) that revealed by the microscope.

As to the first, it is perfectly evident that at many places in all ore bodies, the ore occupies some sort of vague breccia structure, accompanied by many minor folds and contortions of individual layers, some of which have been replaced. Thus, nearly every mass of ore contains numerous scattered, unreplaced, or only partly replaced knots of (a) silicated material, chiefly diopside, (b) relatively pure car-

bonate, (c) granular siliceous material. These are apt to be 3 to 12 inches in size but may be larger or smaller. The diopside and limestone usually contain only minor amounts of scattered sulphide. The siliceous patches usually contain only minor quartz sufficient to outline the fragment faintly, the remaining matrix being replaced by sulphides.

Illustrations of these relations are shown in several photographs in Plates 2 and 3.

The ore zones occupy the most definitely and strongly brecciated areas, but these "breccias" never exactly fulfilled the usual concept of the term, *i.e.*, a zone of crushing with resultant freeing of distinct comminuted particles and the production of visible open spaces. They were more like plastic breccias produced very close to the zone of flowage rather than fracture. Many such healed zones are still evident in the Grenville limestone both in the vicinity of ore bodies and far removed from them. Any effects on porosity or permeability, therefore, were on a microscopic scale and are reflected with some approach to accuracy in the tabulated statistics of the porosity and grain size of specimens from ore bodies.

As to the second point—the microscopic evidence of brecciation or at least of deformation, as a step in the preparation of the ground for ore reception—there is considerable positive evidence although by no means as much as could be desired, and some of it susceptible of other possible interpretations.

We are seeking incontrovertible proof of brecciation on a microscopic scale prior to the introduction of ore, comparable to the concrete visible evidence such as unreplaced folded fragments or bands which indicate by field relations that the vague ore breccias were antecedent to the ore. Unfortunately, the evidence of such microscopic features has been destroyed in a large measure by replacement. Certain details do remain, however (Pls. 8, 9).

Thus calcite (or dolomite) in normal crystalline limestone exhibits excellent straight cleavages and twinning lines. In some ore sections, however, the twinning planes are bent and deformed presumably by movement and pressure. Of the 20-odd Edwards ore specimens listed in Table 5, 15 show definite bending and flexing of the calcite structure, at least 10 of them markedly so. Moreover, several of these specimens contain very little unreplaced carbonate, thus giving no clue to its original condition. Thus about half the indicative specimens show material plastic deformation of calcite. In addition 2 or 3 show the same feature in relation to anhydrite twin lines, and another 2 or 3 show suggestive folding of elongated diopside grains.

Not all of this deformation can be designated as older than the emplacement of ore, for in three of the preceding instances there is strong postore shattering of sphalerite and pyrite by systems of clear-cut fractures healed with talc, serpentine, or secondary carbonate. Possibly this might have produced the distortion in calcite cleavages and twin lines, although probably not in most cases, since the later postore movements produced mainly definite systems of open fractures, a more normal type of brecciation. Still, this could have produced fractures in the more brittle ore and bending in the more plastic gangue. On the whole, however, most of the calcite deformation appears to be older than the ore, on *a priori* reasoning, also supported in certain cases by apparent conformation of ore deposition to the deformed structures.

In addition to bending and flexing of the less competent minerals there is also

FIGURE 1. TYPICAL ORE FACE, EDWARDS
Dark band is ore. Walls are white crystalline limestone with minor serpentine. Lens of unreplaced pure white limestone in ore.

FIGURE 2. ORE FACE, BALMAT MINE
Brecciated, unreplaced bands of white limestone underlie the ore.

FIGURE 3. BANDED SILICATED LIMESTONE, EDWARDS
Light bands are diopside rock, with serpentine limestone between. From this type of rock the ore breccias are believed to have been derived.

VISUAL STRUCTURES ASSOCIATED WITH ORE OCCURRENCES

FIGURE 1. ORE DEPOSITION IN BRECCIATED, SILICATED LIMESTONE, EDWARDS
Dark diagonal streaks are ore, enclosing unreplaced breccia of diopside rock and serpentine limestone. Broken blocks of diopside rock with serpentinized borders in upper right.

FIGURE 2. INTERBANDING OF ORE AND PURE LIMESTONE, EDWARDS
Dark is ore, grading into dark serpentine limestone below. White is pure crystalline limestone.

VISUAL STRUCTURES ASSOCIATED WITH ORE OCCURRENCES

fracturing and granulation of the more competent ones, particularly diopside. This shows definitely in the form of partially granulated diopside grains or shattered grains in which light sulphide mineralization follows these structures to some extent, in about 3 specimens of the set, and more especially in several other thin sections not included in the porosity set but selected for other purposes.

There are occasional examples of the fracturing and granulation of carbonate with related subsequent deposition of sulphides. There are two particularly good examples in the preceding set of ore specimens, and another in an additional set. This related set of 37 slides, all from the Edwards mine, contains 10 which show good evidence of apparently preore deformation of calcite, 2 of which also show similar deformation of mica, and 2 or 3 with evident preore deformation of diopside, as well as several examples less certain of interpretation.

At Balmat, out of the 25 ore specimens in Table 10 and 5 additional mineralized specimens table 8 there is definite bending or granulation of diopside prior to ore deposition in 5 cases, of calcite in 1 of these and 3 others, 1 of the latter showing mica also affected, and probable preore deformation of quartz in 1 additional slide—a total of 9. The evidence in the Balmat set probably is less abundant than at Edwards largely because the replacement by sulphides is more intense and has obliterated more of the evidence.

An additional set of 14 Balmat specimens shows definite deformation of mica in 3 specimens, of calcite in 2 others, of diopside in 1, and an excellent illustration of the shattering of quartz and its healing by sphalerite in still another.

A third possibility may deserve some consideration. The pure limestone with its high porosity may have been the main pathway for ore fluids, and the bordering zones of intermediate porosity and smaller openings have served as precipitating areas. Some objections to this proposition are.

(1) Ore is usually absent in the pure limestone, even in traces, a strange situation if this were the main conduit.

(2) Ore occurs usually on only one side of pure limestone masses. If these had been main channels, it would seem that at least some ore should occur on the opposite side. However, this failure possibly could be explained on the basis of a lateral temperature gradient, with ore deposited only on the cooler side. If the ore fluid entered as vapor rather than as liquid it might be especially likely that condensation would occur on the cooler side, and the small capillary openings would tend to concentrate the resultant liquids there.

CONCLUSIONS

Field and microscopic data make it reasonably clear that the primary ore deposits under consideration were localized in definite channels of micro brecciation. The host rock commonly was an impure silicated limestone rather than a purer and chemically more suitable facies, for the simple physical reason that such heterogeneous mixtures were more susceptible to microbrecciation than pure limestone. In rare instances, however, shattering of such pure limestone was effective and resulted in ore of unusual richness. Highly silicated masses were neither chemically suitable nor

susceptible to microbrecciation. Ore deposition was mainly by substitution for interstitial carbonate although there was minor replacement of other minerals.

Determinations of porosity in conjunction with microscopic study and grain counts indicate that, compared to all adjacent wall rocks excepting the purer limestone, the host rock had a relatively high porosity and fairly large openings. The pure limestone under present temperature-pressure conditions has a higher porosity and larger openings, but deduction from the admittedly very inadequate physical data available suggests either that this high porosity did not exist under the conditions of ore deposition or, if so, that the porosity was disconnected and ineffective; the former explanation is preferred.

The actual porosity of the microbreccias replaced by ore now is and probably was originally somewhere between 1 per cent and 2 per cent, and the average size of openings is estimated at about .0005 mm (half a micron) in width. There were no openings of visible size with any continuity. The ore-bearing medium evidently worked effectively in spaces of this size and apparently did not enlarge, but may even have tended to reduce them as deposition progressed. It was able to function in narrow channelways of microbrecciation producing ore of substantially unvarying quality throughout a vertical range now known to be more than 2000 feet (more than 3000 feet slope length) and doubtless originally several times that distance.

This brings us to the problem of what kind of medium could perform such miracles. Did it fulfill the conventional conception of a hydrothermal solution carrying in uncertain percentages a substantial burden of dissolved mineral matter which it exchanged along its course for the waste products of replacement, chiefly calcium and magnesium carbonates, which were removed to some convenient dumping ground. An opening half a micron in width is in the capillary range and approaches subcapillary limits. Meinzer (1923, p. 22–28) states that the upper limit of capillary openings may be taken approximately at 0.5 mm and the lower perhaps at .0001 to .002 mm or less.

Unfortunately the subject of capillarity and the movement of fluids in microscopic openings seems to have baffled geologists, so that in later treatises discussion of it has been restricted or eliminated. Nevertheless, under any system of computation of width of openings the voids in these rocks are of capillary dimensions, and well down in the range of capillary sizes. For instance if one should adopt the *Metals Handbook* (1939, p. 760) system of estimation of openings, which by its own admission gives the maximum possible width, the average for the most porous rock type might be about 0.1 mm and that for the ore-bearing microbreccias possibly .005 mm, values roughly between the capillary limits. Undoubtedly also some openings might be considerably larger than average, but not for distances of any length or continuity.

The real factor of geologic importance, of course, is permeability rather than porosity. Porosity is important only as affording some insight into probable permeability. Originally the author planned this investigation to include determination of permeability, but the satisfactory accomplishment of this objective proved impossible. Some qualitative permeability tests were conducted in a preliminary way by simple saturation of various specimens of the important rock types with colored liquids. For this purpose three readily available liquids were used: (1) 2 per cent

mercurochrome solution, (2) red india ink, (3) blue fountain ink (Carter's). The india ink proved too gummy and fast-drying and was useless. The other two fluids gave approximately similar results.

Specimens were tested by (1) total immersion, (2) partial immersion. The specimens were pieces of drill cores similar to those used for the porosity determinations. Length of immersion ranged from 2 hours to 10 days. The maximum penetration obtained, even in 10 days, was about a quarter of an inch (for pure crystalline limestone), with an upward rise above the liquid level of about twice this amount. Three-fourths of this was achieved in the first 2 days. On ore the results were slightly less but more uneven. On serpentine limestone penetration was considerably less than on pure limestone. On tremolite schist and gneiss penetration was almost nil (possibly $\frac{1}{64}$ inch). So far as these tests are concerned, permeability is proportioned to the porosity and size of openings as estimated herein. It is also apparent that permeability for an aqueous solution is extremely low.

Permeability in small openings such as these is proportional to the square of the width of opening; thus the importance of any possible error in the estimated widths has been stressed ,especially if they be underestimated. Since no quantitative data seem to exist regarding the actual force necessary to move aqueous solutions capillary openings, large or small, on a geological scale, this objection seems through pointless.

All the rocks considered in this investigation, except those modified by oxidizing processes as illustrated in Tables 13 and 14, are impervious to ordinary ground water except where traversed by visible openings, either joints, or solution channels made by the enlargement of joints. No water seeps from these rocks, and none is transmitted through them except along visible supercapillary openings. Numerous diamond-drill holes filled with water have been cut at vertical depths up to 600 or 700 feet from their collars at the surface, and the water conducted through these holes has been sealed off successfully either by the simple insertion of wooden plugs, by the attachment of a length of casing seated in cement near the collar and fitted with a valve or by ordinary concreting or grouting. A pressure of some hundreds of pounds per square inch, therefore, is insufficient to force ordinary cold water in perceptible volume through a few feet, or probably a few inches of these rocks. Even allowing for a considerably lowered viscosity of water at elevated temperatures, somewhat offset by the load of mineral matter it should be obliged to carry, it is hard to conceive of any pressure sufficient to force substantial volumes of water through many thousands of feet of such material. Not even the full hydrostatic head of a rock column many miles in height seems adequate to overcome the friction of such a conduit. From this standpoint the situation demands a medium of much lower viscosity and less surface tension than ordinary water, much less any thickened version of it in the form of a hydrothermal solution likely to be effective as an ore medium.

Analyzing the available facts from another viewpoint we may consider work actually performed by the ore fluid in the form of ore importation, rock exportation, and wall-rock alteration. Most analyses of such data, based particularly on illustrations from gold-quartz veins, stress the alkaline character of wall-rock alteration, with deposition of carbonates and sericite. In sulphide replacements, es-

pecially of carbonate rocks, development of secondary carbonates, chlorite, phlogopite, talc, and serpentine is more typical. The latter type applies to the deposits here considered, and all the preceding minerals are represented to some degree, especially serpentine, and subordinately talc. Likewise, in very minor amount as fillings of late-stage postore fractures gypsum and even halite occur, accompanied usually by predominant volumes of secondary carbonate, serpentine, and talc.

TABLE 17.—*Calculation of serpentine-ore relations*

	Total length of drill holes in limestone area (in feet)	Per cent serpentine in total footage	Volume of ore in total footage	Approximate per cent sulphides in ore	Approximate per cent sulphides in total footage
Edwards	6003	4.06	362	30	2
Balmat	2337	3.14	341	50	7

Within the area of Plates 1 and 10 the author has checked over all drill holes from which the specimens for porosity determinations were obtained and has logged the holes with special reference to a visual estimate of the amount of the most important alteration product, serpentine. The results are presented in Table 17.

At Edwards, therefore, within the limits of the mapped area approximately 2 volumes of serpentine were formed at the same level for every volume of sulphide emplaced. At Balmat the figures give a much higher ratio of sulphides to serpentine but here the drilling is confined too closely to the strictly ore-bearing area, and results would be considerably shifted toward correspondence with Edwards if longer holes had penetrated the larger and less productive area of country rock farther from the ore bodies. Some allowance also should be made for an appreciably larger amount of talc at Balmat, perhaps half as great as the volume of serpentine, or possibly even more.

The chief significance of both talc and serpentine so far as composition of ore solutions are concerned is that they represent addition of water and elimination of lime. The water content of serpentine is approximately 13 per cent, of talc only about 5 per cent. Even allowing for serpentine at a ratio to sulphides of 2:1 by weight rather than volume, the amount of water fixed in the wall rock is comparatively small, only about a quarter of the weight of sulphides. Of course this figure might be modified in favor of water by assuming that the serpentine scattered over miles of unproductive area between known mines should be taken into account, or that the vertical range of serpentine and allied alteration products may be much greater than that of ore, although there is no proof of this. Such modifications in themselves scarcely add up to an overwhelming flood of aqueous liquid.

Likewise, in the observable effects of carbonate redistribution there is little evidence of action by any tremendous volume of water. Solution cavities in the deeper areas of either mine are virtually unknown. Obvious secondary carbonate is fairly common in postore fractures but insignificant in volume. In a limestone formation it is difficult to say how much carbonate aside from visible fracture fillings may in some way be secondary, but even if it is a substantial amount it can only have replaced

other substances, the removal of which was required thereby. The amount of secondary carbonate disposable in fractures must be of the order of some fraction of 1 per cent of the rock in and around the ore bodies.

The history of the formation of these ore deposits seems to involve the following interpretable events.

(1) A series of sedimentary rocks including impure limestones was deeply buried, intensely folded, and regionally metamorphosed; the limestone members became crystalline dolomitic marble in part, irregularly mixed and interlayered with silicate matter, chiefly diopside and tremolite, much of it in bands representing distorted beds.

(2) Granitic intrusions invaded the metamorphosed sediments, extensively granitizing the gneisses but usually invading the limestones only to a minor extent in the form of pegmatite. The pegmatites caused variable degrees of silication and silicification of the invaded limestone and were themselves so modified by reaction with the wall rock that it is difficult to tell, in many cases, where silicification ends and pegmatite begins. There is abundant pegmatization in the deeper levels at Edwards, little or none as yet at Balmat, but evidences of it in the form of intensely altered bands probably is suggestive.

Probably the microbreccias were formed, or at least received their significant shattering at or just followig this period, and ore deposition ensued soon or concomitantly.

(3) Ore deposition was initiated by the introduction of pyrite in the microbrecciated zones followed shortly by abundant dark sphalerite, probably indicative of a high temperature. Pyrite deposition tapered off. The deposition of sphalerite ended with a slight amount of late-stage, light-yellow sphalerite suggestive of falling temperature. A little galena ended the sulphide phase.

Ore deposition was associated with strong alteration of wall rock to serpentine and talc and an uncertain amount of transport and redeposition of carbonate. This alteration was partly contemporaneous and certainly in part later than the ore deposition. Minor fracturing accompanied this process resulting in numerous cracks in sulphides healed by talc, serpentine, secondary carbonate.

(4) In rare instances the latest phase of stage 3 was the filling of certain postore fractures with veinlets of gypsum and halite. Open spaces in these fractures may contain saline water characterized by predominant calcium and magnesium chlorides, with minor sulphates and subordinate sodium chloride, clearly the residual solution from which the gypsum and halite were deposited.

As with most ore deposits elsewhere the evidence indicates that ore deposition was concentrated intensely into a period geologically brief and never repeated.

This study admittedly proves little, if anything, as to the nature of the ore fluid. In the author's opinion an ore medium was probably required which was considerably more fluid than water, and at the same time much more concentrated in metallic ingredients than a hydrothermal vehicle. This practically resolves itself into the postulate of a metallic vapor consisting mainly of the materials deposited, namely, iron, zinc, and sulphur—with a little lead and barium probably, accompanied by a distinctly subordinate amount of water; a considerable part of the water remaine

fixed in the vicinity in the form of hydrous alteration products, chiefly serpentine and talc.

This ore vapor, substituting itself in the matrix of the microbreccias for carbonate, must have forced the migration of the carbonate either to higher levels now eroded or into minute redistribution in the pores and fractures of the surrounding wall rocks. If the possibility that the ore fluid was a vapor is entertained, then the elimination of carbonate by gaseous transfer may also be implied although perhaps not necessarily. Many, doubtless, will regard these speculations as unwarranted.

The foregoing speculations suggest temperatures of ore deposition considerably higher than have been favored in recent years by the protagonists of hydrothermal solutions, among whom, until the later stages of this investigation, the author included himself. They also pose a host of problems far beyond the scope of this investigation. These the author has attacked comprehensively in a separate paper not yet published. In the sequel to the present study the possibilities and probabilities of vapor transfer are covered from many angles, and support therefore is found in geologic principles of much broader significance and more general application than seem inherent in the study of porosity and permeability.

REFERENCES CITED

Bain, G. W. (1936) *Mechanics of metasomatism*, Econ. Geol., vol. 31, p. 505–526. *See* especially Figure 5, p. 520.

——— (1941) *Measuring grain boundaries in crystalline rocks*, Jour. Geol., vol. 49, p. 199–206.

Birch, Francis (Editor) (1942) *Handbook of physical constants*, Geol. Soc. Am., Spec. Papers, 36.

Brown, J. S. (1936a) *Structure and primary mineralization of the zinc mine at Balmat, N. Y.*, Econ. Geol., vol. 31, p. 233–258.

——— (1936b) *Supergene sphalerite, galena and willemite at Balmat, N. Y.*, Econ. Geol., vol. 31, p. 331–354.

Metals Handbook, 1936, p. 754–767. *Austenite grain size in steel.*

——— (1940) *Factors of composition and porosity in lead-zinc replacements of metamorphosed limestone*, Am. Inst. Min. Metall. Eng., Tech. Pub. no. 1194. *See also* Transactions (1941), vol. 144, p. 253–263.

Washburn, Edward W. (Editor) (1928) *International critical tables*, McGraw-Hill, 7 vols. and index, 1926–1933.

Meinzer, O. E. (1923) *Occurrence of ground water in the United States*, U. S. Geol. Survey, W.S. Paper 489.

St. Joseph Lead Company, Balmat, New York.

Manuscript Received by the Secretary of the Society, December 6, 1944.
Project Grant 414/42.

PLATE 4.—PHOTOMICROGRAPHS OF TYPICAL ROCK AND ORE TEXTURES AS RELATED TO GRAIN COUNTS

Figure

1. Portion of a section of typical crystalline limestone, Edwards Mine. Used for grain counts. Calcite with a little diopside.
2. Crystalline limestone, Balmat Mine.

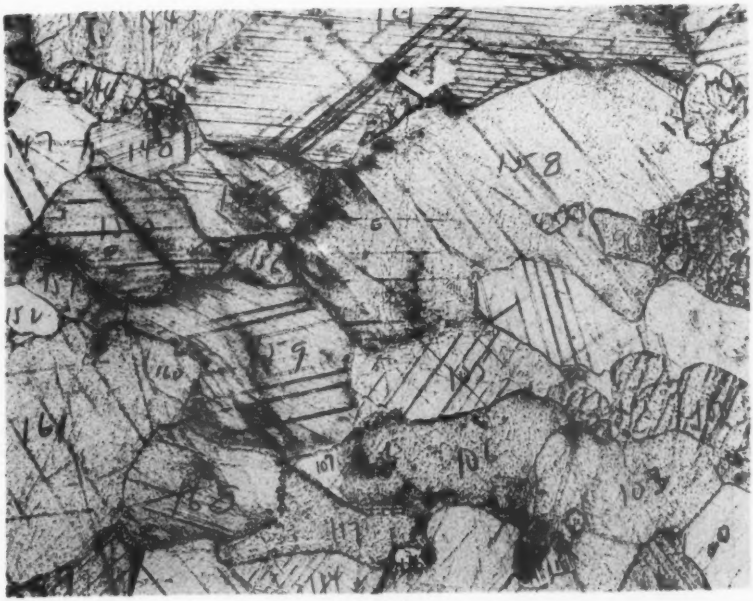


FIGURE 1

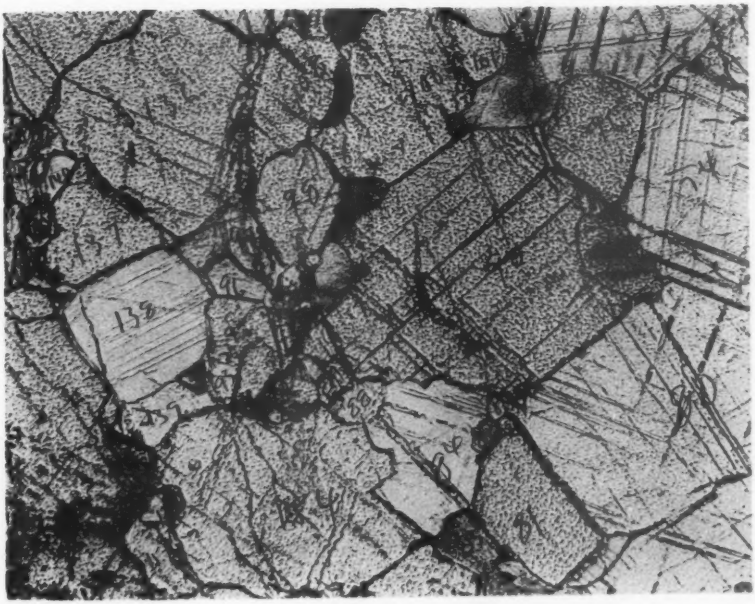


FIGURE 2

PHOTOMICROGRAPHS OF TYPICAL ROCK AND ORE TEXTURES AS RELATED TO GRAIN COUNTS

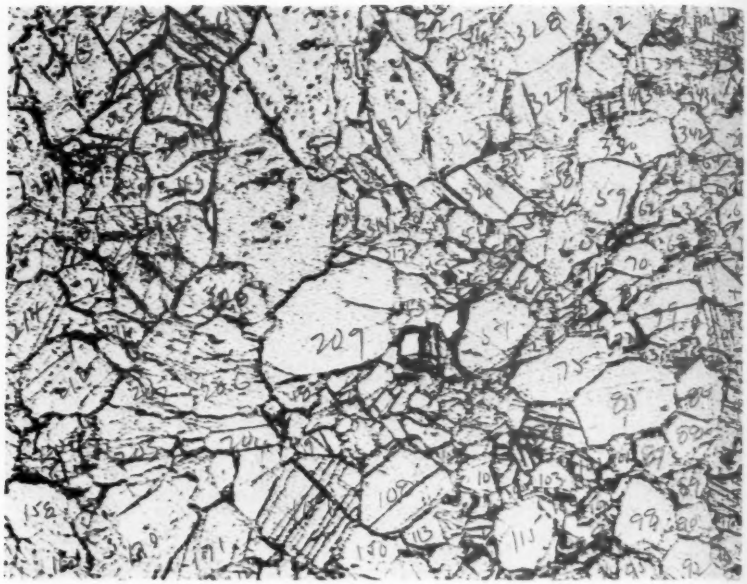


FIGURE 1

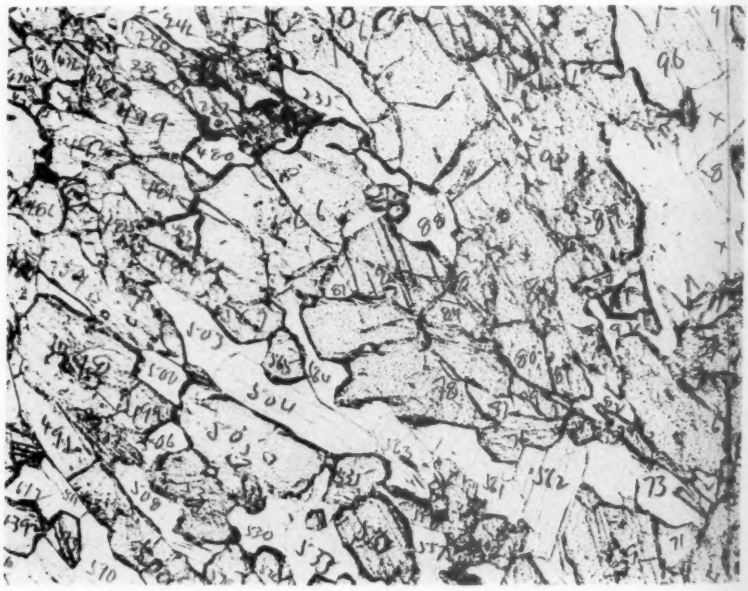


FIGURE 2

PHOTOMICROGRAPHS OF TYPICAL ROCK AND ORE TEXTURES AS RELATED TO GRAIN COUNTS

PLATE 5.—PHOTOMICROGRAPHS OF TYPICAL ROCK AND ORE TEXTURES AS RELATED TO GRAIN COUNTS

Figure

1. Typical diopside rock, Edwards Mine. Used for grain counts.
2. Silicated limestone (diopside and mica), Balmat Mine.

PLATE 6.—PHOTOMICROGRAPHS OF TYPICAL ROCK AND ORE TEXTURES AS RELATED TO GRAIN COUNTS

Figure

1. Serpentine limestone, Edwards Mine. Serpentine after diopside, with calcite.
2. Tremolite rock, Balmat Mine.

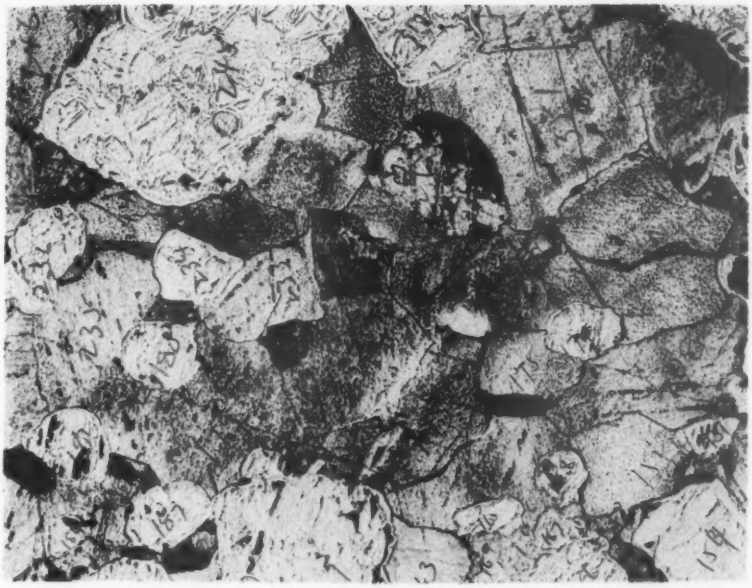


FIGURE 1

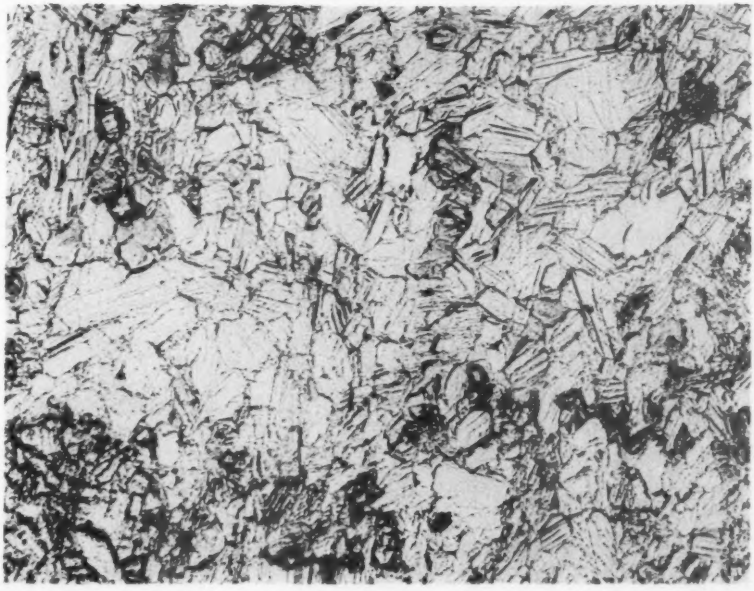


FIGURE 2

PHOTOMICROGRAPHS OF TYPICAL ROCK AND ORE TEXTURES AS RELATED TO GRAIN COUNTS

FIGURE 1

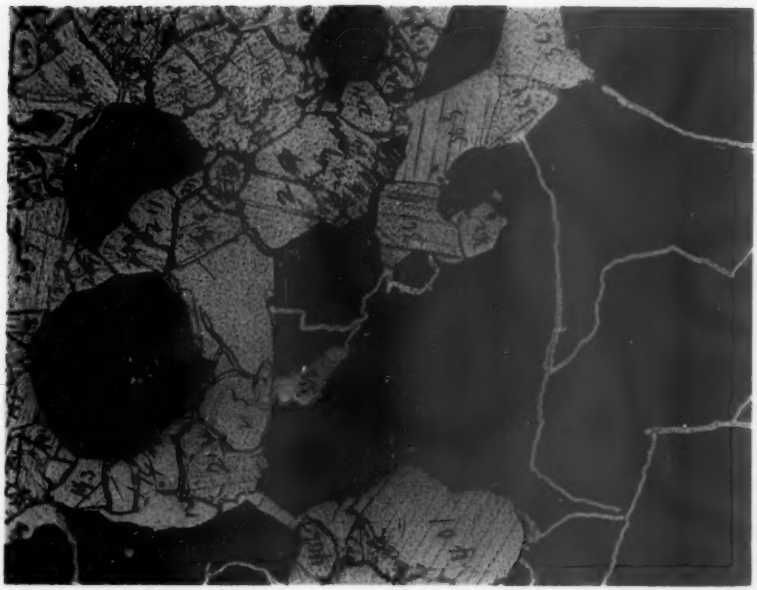


FIGURE 2

PHOTOMICROGRAPHS OF TYPICAL ROCK AND ORE TEXTURES AS RELATED TO GRAIN COUNTS

PLATE 7.—PHOTOMICROGRAPHS OF TYPICAL ROCK AND ORE TEXTURES AS RELATED TO GRAIN COUNTS

Figure

1. Typical ore as used for grain counts, Edwards Mine. Black is sphalerite; rough gray, pyrite; gangue chiefly calcite.
2. Ore, Balmat Mine. Sphalerite, diopside, and minor calcite.

PLATE 8.—PHOTOMICROGRAPHS ILLUSTRATING EVIDENCE FOR PREORE AND POSTORE DEFORMATION. (× 35)

Figure

1. Bent crystal of diopside. Pyrite (gray) of later deposition has been molded on the crystal. Balmat Mine.
2. Split diopside crystal. Pyrite deposited in crack. Dull black is sphalerite. Balmat Mine.
3. Shattered and granulated diopside. Sphalerite deposited in shattered zones. Balmat Mine.
4. Shattered diopside. Contains later galena (dead black) and sphalerite (dull black) in shattered zones. Rough gray is pyrite. Balmat Mine.
5. Bent calcite. Later sphalerite (dull black) seems to conform to the bending. Edwards Mine.
6. Bent and deformed calcite replaced by sphalerite. Serpentine (after diopside) seamed by sphalerite. The sphalerite filled cracks in diopside which was later replaced by serpentine. Edwards Mine.

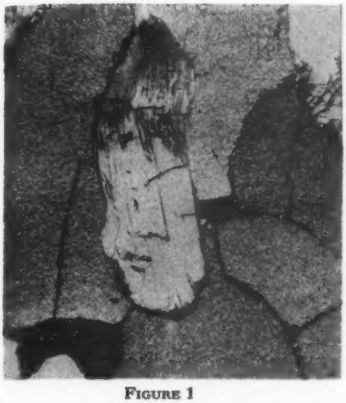


FIGURE 1

FIGURE 2

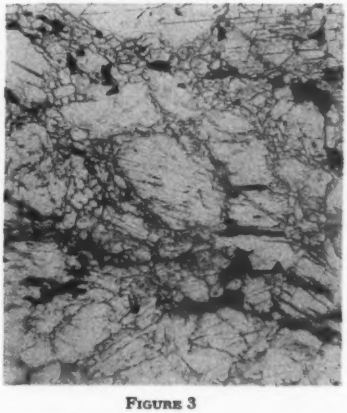


FIGURE 3

FIGURE 4

FIGURE 5

FIGURE 6

PHOTOMICROGRAPHS ILLUSTRATING EVIDENCE FOR PREORE AND POSTORE DEFORMATION. (X 35)

FIGURE 1

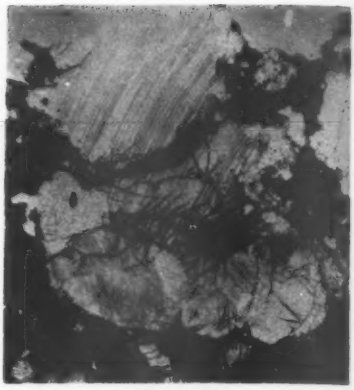


FIGURE 2

FIGURE 3

FIGURE 4

FIGURE 5

FIGURE 6

PHOTOMICROGRAPHS ILLUSTRATING EVIDENCE FOR PREORE AND POSTORE DEFORMATION. (X 35)

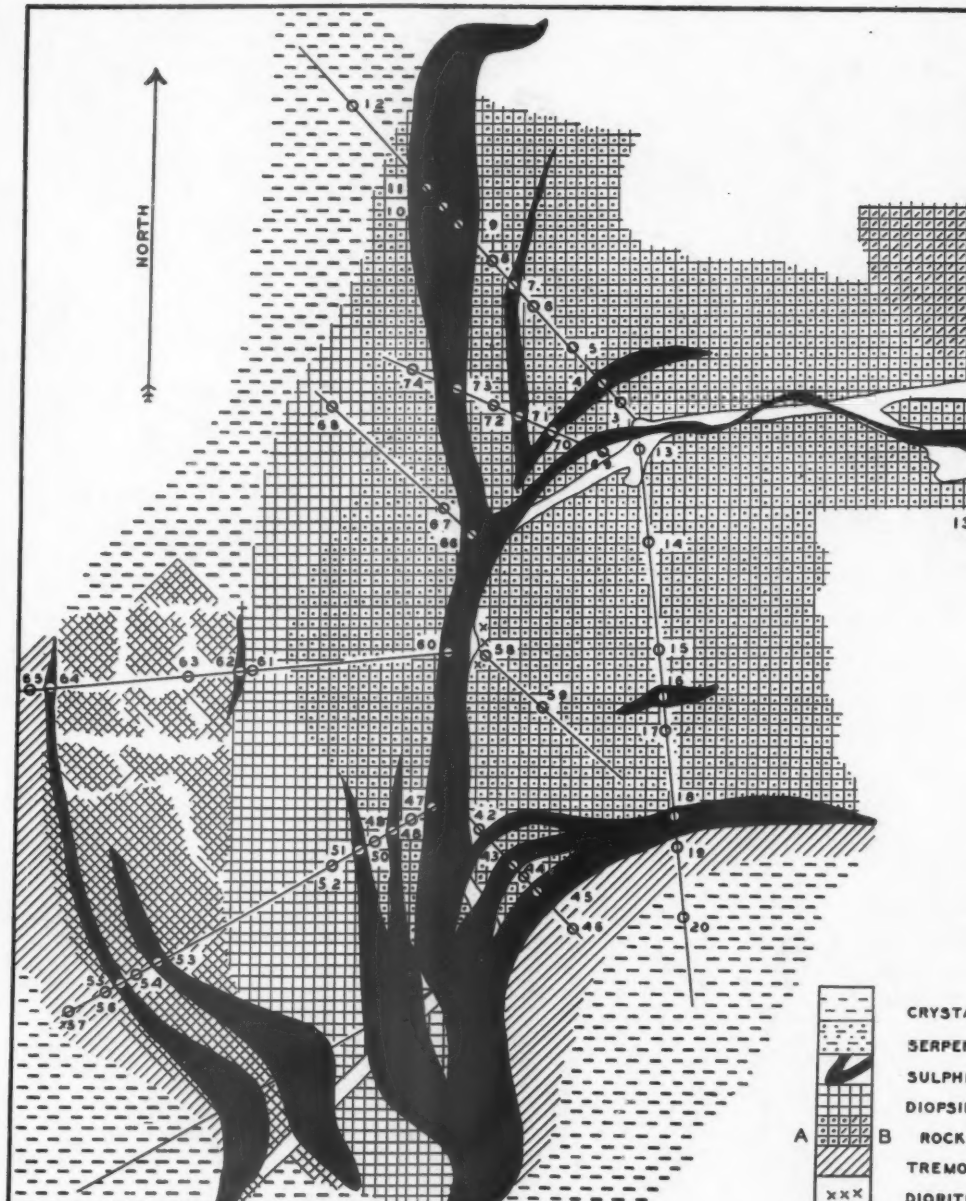
PLATE 9.—PHOTOMICROGRAPHS ILLUSTRATING EVIDENCE FOR PREORE AND POSTORE DEFORMATION. (× 35)

Figure

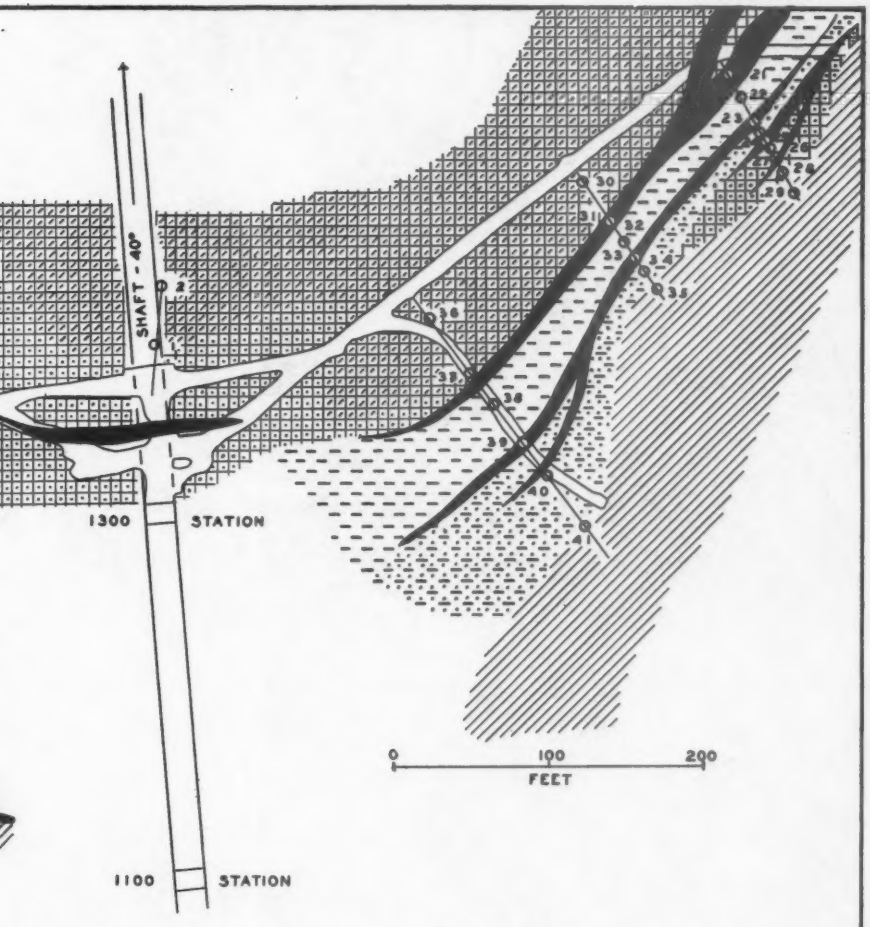
1. Bent calcite to which pyrite and sphalerite conform. Shattered diopside seamed by sphalerite. Edwards Mine.
2. Bent and shattered calcite. Replaced by later sphalerite. Edwards Mine.
3. Bent mica sheets with sphalerite between the leaves (center). Also deformed calcite. Edwards Mine.
4. Shattered quartz (center). Shattered zones healed by sphalerite (center: sphalerite, dark gray). Balmat Mine.
5. Postore fracturing cutting sphalerite, pyrite, and diopside. Healed with serpentine. Edwards Mine.
6. Postore shattering of pyrite and sphalerite. Healed by serpentine and banded calcium carbonate. Edwards Mine.

All photomicrographs by G. W. Bain

P. 547-550 taken out for index



GEOLOGY AND POROSITY DATA, 1300-FOOT



LEGEND

	AVERAGE POROSITY PER CENT	AVERAGE GRAINS SQ. CM.	AVERAGE OPENINGS M. M.	EDWARDS COMPARISON
CRYSTALLINE LIMESTONE SERPENTINIZED LIMESTONE	1.84*	157	.00197	.00128
SULPHIDE ORE BODIES	1.36	535	.00048	.00057
DIOPSIDE ROCK B — A – SERPENTINIZED B – MICACEOUS	1.31	1657	.00018	.00024
TREMOLITE ROCK	1.34	2908	.00012	
DIORITIC INTRUSIVE	0.97	34500	.000013	
HEMATITE – CHLORITE ALTERATION	8.93	?	.00000?	

, 1300-FOOT LEVEL, BALMAT MINE